Toxic Treatments, *In Situ* Steam/Hot-Air Stripping Technology

Applications Analysis Report

Risk Reduction Engineering Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The information in this document has been funded by the U.S. Environmental Protection Agency under Contract No. 68-03-3485 and the Superfund Innovative Technology Evaluation (SITE) Program. It has been subjected to the Agency's peer review and administrative review, and it has been approved for publication as a USEPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

Foreword

The Superfund Innovative Technology Evaluation (SITE) Program was authorized by the 1986 Superfund Amendments and Reauthorization Act (SARA). The program is a joint effort by EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) to enhance the development of hazardous waste treatment technologies necessary for implementing new cleanup standards that require greater reliance on permanent remedies. This is accomplished by performing technical demonstrations that provide engineering and economic data on selected technologies.

This project consists of an analysis of the Toxic Treatments (USA), Inc., (TTUSA) *in situ* steam/hot-air stripping technology. A Demonstration Test took place at a former bulk liquid waste storage facility, located at the GATX Annex Terminal site in San Pedro, California. The purpose of the demonstration was to obtain information on the performance and cost of the process in order to assess the technology's potential application at other hazardous waste sites. The Technology Evaluation Report describes the field activities and laboratory results. This Applications Analysis Report provides an interpretation of the available data and a discussion of the potential applicability of the technology.

Additional copies of this report may be obtained at no charge from EPA's Center for Environmental Research Information, 26 West Martin Luther King Jr. Drive, Cincinnati, Ohio 45268, using the EPA document number found on the report's front cover. Once this supply is exhausted, copies can be purchased from the National Technical Information Service, Ravensworth Building, Springfield, Virginia 22161, (703) 487-4600. Reference copies will be available in the Hazardous Waste Collection at EPA libraries. Information regarding the availability of other reports can be obtained by calling the SITE Clearinghouse Hotline at (800) 424- 9346 or (202) 382-3000 in Washington, D.C.

_____
E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

Abstract

This document is an evaluation of the performance of the Toxic Treatments (USA), Inc., (TTUSA) *in situ* steam/hot-air stripping technology and its applicability as an on-site treatment technique for hazardous waste site soil cleanup of volatile and semivolatile contaminants. Both technical and economic aspects of the technology were examined.

A demonstration of the TTUSA stripping technology was conducted beginning in the fall of 1989 at the GATX Annex Terminal site located at the Port of Los Angeles, California. Operational data and sampling and analysis information were carefully compiled to establish a data base against which other available data, as well as the vendor's claims for the technology, could be compared and evaluated. Conclusions concerning the technology's suitability for use in stripping the range of contaminants at this test site were reached, and extrapolations regarding applications at other sites with different contaminants and soil types were made.

The following conclusions were derived primarily from the Demonstration Test results and supported by other available data: (1) the process removed volatile organic compounds at an average efficiency of approximately 85% from the contaminated soils tested; (2) the technology reduced the level of semivolatile compounds in the soil by approximately 50%; (3) there was no evidence of significant downward migration of contaminants based on qualitative testing; (4) fugitive emissions from the soil during and after treatment were low; and (5) the process is capable of removing volatile organic compounds *in situ* in relatively short time periods with competitive economics.

Contents

Tables

Figures

Abbreviations and Symbols

ARAR	Applicable or Relevant and Appropriate Requirements
BDAT	Best Demonstrated Available Technology
BTU	British Thermal Unit
C	Celsius
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CFR	Code of Federal Regulations
CWA	Clean Water Act
DHS	Department of Health Services (California)
DOT	Department of Transportation
EPA	Environmental Protection Agency
F	Fahrenheit
FID	Flame Ionization Detector
ft	Feet
gal	Gallons
GATX	GATX Terminals Corporation
GC	Gas Chromatograph
g	Gram
gpm	Gallons per minute
kg	Kilograms
kW	Kilowatts
kWh	Kilowatt-hours
lb	Pounds
L	Liters
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level and Goal
MDL	Method Detection Limit
mg	Milligrams
μg	Micrograms
min	Minutes
ml	Milliliters
NPDES	National Pollutant Discharge Elimination System
NPL	National Priority List
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
OVA	Organic Vapor Analyzer
PAH	Polynuclear Aromatic Hydrocarbon
ppb	Parts per billion
ppm	Parts per million
ppmV	Parts per million Volume
psig	Pounds per square inch gauge
%	Percent
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
s	Seconds
SAIC	Science Applications International Corporation

SARA	Superfund Amendment and Reauthorization Act
scfm	Standard cubic feet per minute
SCAQMD	Southern California Air Quality Management District
SDWA	Safe Drinking Water Act
SITE	Superfund Innovative Technology Evaluation
SW	Solid Waste
SVC	Semivolatile Compound
TCLP	Toxicity Characteristic Leaching Procedure
THC	Total Hydrocarbons
TSD	Treatment, Storage, and Disposal
TTUSA	Toxic Treatments (USA), Inc.
VAC	Voltage Alternating Current
VOC	Volatile Organic Compound

Acknowledgments

Section 1
Executive Summary

Introduction

This report summarizes the findings of an evaluation of the *in situ* steam/hot-air stripping technology developed by Toxic Treatments (USA), Inc. (TTUSA). The study was conducted under the Superfund Innovative Technology Evaluation (SITE) Program. A Demonstration Test of the technology was performed by EPA as part of this Program. The results of this test, along with supporting data from other testing performed by TTUSA and background information from literature constitute the basis for this report.

The TTUSA technology is a mobile *in situ* stripping process that utilizes steam and hot air to treat soils contaminated with volatile compounds without the need for excavation. Previous experience with steam/hot-air stripping systems has demonstrated that a large fraction of the volatile compounds can be stripped from the soil and that semivolatile compound levels can be reduced to some extent. The level of contaminant removal is dependent on the following factors: contaminants present, treatment time, soil conditions, chemical reactions, and soil binding.

Conclusions

A number of conclusions may be drawn from the evaluation of this innovative technology. The most extensive data were obtained during the SITE Demonstration Test; data from other testing activities have been evaluated in relation to SITE Program objectives. The conclusions drawn are:

- The process can remove a significant amount of VOCs from contaminated soil.

- Treatment of a contaminated area can successfully extend into the saturated zone. Percent removal and treatment rates are comparable to treatment in the vadose zone.

- The system operates in a batch-like fashion such that the amount of volatile contaminants removed from the soil is a function of treatment time.

- The *in situ* steam/hot-air stripper can also reduce the level of semivolatile organic compounds in the soil treatment block. Although the semivolatiles detected prior to treatment are not present in the post-treatment soil, they remain unaccounted for elsewhere in the process.

- Data obtained from qualitative dye studies in and below the treatment area do not indicate downward migration of organic contaminants to below the zone of treatment.

- Total fugitive emissions from the soil during and after treatment are low. Process fugitive emissions are also low apart from emissions during regeneration of the gas-phase carbon beds. Recent design modifications to the process have alleviated this problem.

- The mixing action of the augers does not produce a homogeneous area of treatment. Chemical analyses for volatile and semivolatile contaminants and dye test data indicate that substantial variations occur within treated soil blocks.

- The treatment process did not affect the physical properties of the tested soil to any significant extent. Neither moisture content nor bulk density of the soil are influenced to any statistical degree by the addition of steam to the treatment area.

- The TTUSA process can strip VOCs from a variety of soil types. Soils with a high clay content have a binding effect on the compounds which results in long treatment time requirements for this type of soil. Sandy soils lend themselves to much shorter remediation times than clay soils. Soils with moderate amounts of clay can be treated readily by the TTUSA process. Increased clay content decreases economical feasibility of treatment.

- VOCs with high boiling points, such as tetrachloroethene, require a greater soil block treatment time than volatile compounds with low boiling points such as methylene chloride.

- The unit is transportable on 5 tractor/trailer rigs, 1 of which is deemed an oversize load. Assembly and disassembly times are each estimated at one week.

- The *in situ* steam/hot-air stripper is an attractive economical alternative to other soil stripping technologies for sites that require short remediation times. The cost of operating the system is strongly dependent on the treatment time required per block.

Successful operation of the *in situ* steam/hot-air stripper is limited by several logistical considerations. Depending on the treatment area, site preparation activities may be extensive or even prohibitive. The treatment area must be graded to a minimum slope of 1% and must be greater than 0.5 acre in size (at least 2 acres total site area). The treatment area must be compacted sufficiently to support the unit's weight. All

underground obstacles larger than 12-in diameter and overhead wires lower than 30 ft must be removed.

Results

- For treatment in the vadose zone to a depth of 5 ft, the level of volatile contaminants in the soil can be reduced to an average concentration less than the target level of 100 ppm. The average removal efficiency of the TTUSA process on volatile contaminants is approximately 85%. For treatment which extends into the saturated zone and below the zone of contamination, the level of volatile contaminants in the soil can also be reduced to an average concentration less than the target level of 100 ppm.

- The amount of semivolatile contaminants in the soil can apparently be reduced by approximately 50%. The fate of these semivolatiles remains unknown.

- The largest contributor to soil fugitive emissions is the block that has just been treated, after the shroud has been moved to a new position. This block has its highest emission rates immediately upon completion of treatment, but these rates decrease rapidly with time.

- Moisture content and bulk density appear to change slightly as a result of treatment, however this effect is not statistically significant. Particle density, which was evaluated only during the SITE Demonstration, was found to increase by an average of 6.5%.

- During normal operation of the stripper, the process can achieve an on-line treatment time factor of approximately 70%.

- For a treatment rate of 3 yd^3/hour and an on-line factor of 70%, the cost based on an economic analysis is \$317/yd^3; if the treatment rate can be increased to 10 yd^3/hr with the same on-line factor, the cost drops to \$111/yd^3.

Section 2
Introduction

The SITE Program

In 1986, the EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) established the Superfund Innovative Technology Evaluation (SITE) Program to promote the development and use of innovative technologies to clean up Superfund sites across the country. Now in its fourth year, SITE is helping to provide the treatment technologies necessary to implement new federal and state cleanup standards aimed at permanent remedies, rather than quick fixes. The SITE Program is composed of three major elements: the Demonstration Program, the Emerging Technologies Program, and the Measurement and Monitoring Technologies Program.

The major focus has been on the Demonstration Program, which is designed to provide engineering and cost data on selected technologies. To date, the demonstration projects have not involved funding for technology developers. EPA and developers participating in the program share the cost of the demonstration. Developers are responsible for demonstrating their innovative systems at chosen sites, usually Superfund sites. EPA is responsible for sampling, analyzing, and evaluating all test results. The result is an assessment of the technology's performance, reliability, and cost. This information will be used in conjunction with other data to select the most appropriate technologies for the cleanup of Superfund sites.

Developers of innovative technologies apply to the Demonstration Program by responding to EPA's annual solicitation. EPA will also accept proposals at any time when a developer has a treatment project scheduled with Superfund waste. To qualify for the program, a new technology must be at the pilot or full scale and offer some advantage over existing technologies. Mobile technologies are of particular interest to EPA.

Once EPA has accepted a proposal, EPA and the developer work with the EPA Regional Offices and state agencies to identify a site containing wastes suitable for testing the capabilities of the technology. EPA prepares a detailed sampling and analysis plan designed to thoroughly evaluate the technology and to ensure that the resulting data are reliable. The duration of a demonstration varies from a few days to several months, depending on the length of time and quantity of waste needed to assess the technology. After the completion of a technology demonstration, EPA prepares two reports, which are explained in more detail below. Ultimately,

the Demonstration Program leads to an analysis of the technology's overall applicability to Superfund problems.

The second principal element of the SITE Program is the Emerging Technologies Program, which fosters the further investigation and development of treatment technologies that are still at the laboratory scale. Successful validation of these technologies could lead to the development of a system ready for field demonstration. The third component of the SITE Program, the Measurement and Monitoring Technologies Program, provides assistance in the development and demonstration of innovative technologies to better characterize Superfund sites.

SITE Program Reports

The analysis of technologies participating in the Demonstration Program is contained in two documents: the Technology Evaluation Report and the Applications Analysis Report. The Technology Evaluation Report contains a comprehensive description of the demonstration sponsored by the SITE program and its results. It gives a detailed description of the technology, the site and waste used for the demonstration, sampling and analysis during the test, the data generated, and the quality assurance program.

The scope of the Applications Analysis Report is broader and encompasses estimation of the Superfund applications and costs of a technology based on all available data. This report compiles and summarizes the results of the SITE demonstration, the vendor's design and test data, and other laboratory and field applications of the technology. It discusses the advantages, disadvantages, and limitations of the technology.

Costs of the technology for different applications are estimated based on available data on pilot- and full-scale applications. The report discusses the factors, such as site and waste characteristics, that have a major impact on costs and performance.

The amount of available data for the evaluation of an innovative technology varies widely. Data may be limited to laboratory tests on synthetic waste, or may include performance data on actual wastes treated at the pilot or full scale. In addition, there are limits to conclusions regarding Superfund applications that can be drawn from a single field demonstration. A successful field demonstration does not necessarily

3

assure that a technology will be widely applicable or fully developed to the commercial scale. The Applications Analysis attempts to synthesize whatever information is available and draw reasonable conclusions. This document will be very useful to those considering the technology for Superfund cleanups and represents a critical step in the development and commercialization of the treatment technology.

Key Contacts

For more information on the demonstration of the TTUSA technology, please contact:

1. EPA Project Manager concerning the SITE demonstration:

   Mr. Paul de Percin
   U.S. EPA
   Risk Reduction Engineering Lab.
   26 W. Martin Luther King Drive
   Cincinnati, OH 45268
   (513) 569-7797

2. Regional contact concerning the San Pedro, California site:

   Ms. Julia Bussey
   California Dept. of Health Services
   Toxic Substances Control Division
   4250 W. Broadway, Suite 360
   Long Beach, CA 90802
   (213) 590-4930

3. Vendor concerning the process:

   Dr. Phil La Mori
   Toxic Treatments (USA), Inc.
   151 Union Street, Suite 155
   San Francisco, CA 94111
   (415) 391-2113

Section 3
Technology Applications Analysis

Introduction

This section of the report addresses the applicability of the Toxic Treatments (USA), Inc. or TTUSA process to various potential soil contaminants and site conditions based primarily upon the results obtained from the SITE demonstration as well as additional TTUSA applications test data. Since the results of the Demonstration Test provide the most extensive data base, conclusions on the technology's effectiveness and its applicability to other potential cleanups are based primarily on those results, which are presented in detail in the Technology Evaluation Report. Additional information on the TTUSA technology, including vendor's claims, a brief process description, a summary of the Demonstration Test Results, and reports on outside sources of data using the TTUSA technology are provided in Appendices A-D.

Following are the overall conclusions drawn on the TTUSA technology. The "Technology Evaluation" subsection discusses the available data from the Demonstration Test, TTUSA, and literature. This subsection also provides more details on the conclusions and applicability of the TTUSA process.

Conclusions

In general, stripping technologies operate to remove a select species from a given media. This technology moves from treatment block to treatment block to remove VOCs from soil at a contaminated site; it also reduces the level of semivolatile organic contamination, although the mechanism of reduction and ultimate fate of the semivolatiles is unknown. Long-term effectiveness of this process is promising since the source of contamination is removed or significantly reduced.

The overall removal efficiencies for volatile compounds by the TTUSA *in situ* steam/hot-air stripping technology are high; the efficiencies for reducing (not removing) the amount of semivolatiles present in the soil are moderate. Post-treatment levels of contamination are dependent on treatment time and operational technique, but low levels of volatile contamination can be attained without significant downward migration, fugitive emissions, or effects on the physical properties of the soil.

The conclusions drawn from reviewing data on the TTUSA *in situ* steam/hot-air stripping process are:

- The process can strip a substantial amount of VOCs from contaminated soil.

- Treatment of a contaminated area can successfully extend into the saturated zone. Percent removal and treatment rates are comparable to treatment in the vadose zone.

- Batch operation of the system allows the amount of volatile contaminants removed from the soil to be varied as a function of treatment time.

- The *in situ* steam/hot-air stripper can reduce the level of semivolatile organic compounds in the treated soil. However, the fate of semivolatile contaminants has not been determined.

- Qualitative data obtained from dye studies conducted in and below the treatment area do not indicate downward migration of organic contaminants to below the zone of treatment.

- Total fugitive emissions from the soil as a result of treatment are low. Process fugitive emissions are also low apart from emissions during regeneration of the gas-phase carbon beds. The design of the carbon bed system has been modified to alleviate this problem.

- The mixing action of the augers does not produce a homogeneous area of treatment. In fact, the treated block is very heterogeneous in nature. Chemical analyses for volatile and semivolatile contaminants and dye test data indicate that substantial variations occur within treated soil blocks.

- The treatment process does not affect the physical properties of the soil to any significant extent. Although treatment is conducted with steam, neither moisture content nor bulk density of the soil are influenced.

- The TTUSA process can strip VOCs from a variety of soil types. The impact of soil type is more economic than operational, i.e., soils with a high clay content have a binding effect on the compounds, resulting in long treatment time requirements for this type of soil; sandy soils lend themselves to much shorter remediation times than clay soils.

- VOCs with high boiling points, such as tetrachloroethene, require a greater block treatment time than volatile compounds with low boiling points such as methylene chloride.

Several site limitations must be effectively addressed to facilitate successful operation of the *in situ* steam/hot-air stripper. Depending on the treatment area, site preparation activities may be extensive or even prohibitive. The treatment area must be graded to a minimum slope of 1% and must be greater than 0.5 acre in size (at least 2 acres total site area). The treatment area must be compacted substantially to accommodate support for the unit's weight. All underground obstacles larger than 12-inch diameter and overhead wires lower than 30 feet must be removed.

Technology Evaluation

The following discussions utilize all available information to provide more detailed conclusions on the process, particularly as related to chemical and operational test results. A summary of the data from the Demonstration Test is presented in Appendix B; data from other tests conducted on the technology may be found in Appendix D, "Case Studies". Detailed estimates regarding the cost of using this technology are presented in a separate section of this report, Section 4, "Economic Analysis".

Chemical Test Results

The TTUSA *in situ* steam/hot-air stripping technology is designed to remove VOCs from contaminated soil. Testing activities have demonstrated that the process can effectively meet this design criteria; an average removal efficiency of approximately 85% was achieved during the SITE Demonstration Test for VOCs. Tests have also revealed a second, unexpected consequence of the stripping process: it reduces the level of semivolatile organic compounds in the soil, to a moderate degree. The *in situ* steam/hot-air stripper has demonstrated the ability to diminish the level of semivolatiles by approximately 50%, although the fate of these semivolatiles was not determined.

The SITE Demonstration Test was conducted in Area A of the GATX Annex Terminal site. Sampling activities took place in a 12-block test area where the contaminated soil was treated only to the water table (to a depth of 5 feet) and in a 6-block test area where an alternative treatment protocol was implemented to treat the soil into the saturated zone and below the full zone of contamination (to depths ranging from 8 to 11 feet). Screening data indicated that the selected test blocks were heavily contaminated with both volatile and semivolatile contaminants and that the soil in both areas had a high clay content. This provided a demanding test on the ability of the equipment to remove substantial amounts of contamination from the soil. On the other hand, high removal efficiencies were relatively easy to obtain due to the high initial concentrations of the contaminants.

Demonstration Test pre-treatment soil cores obtained from the 12-block test area showed average initial levels of contamination from 28 parts per million (ppm) up to 1,130 ppm total VOCs. Post-treatment cores in this area indicated significant decreases in the level of volatile organics, with average levels ranging from 12 up to 196 ppm total VOCs. Based on composite samples, the average concentration in the 12-block test area was 71 ppm with a standard deviation of 80 ppm. The 95% confidence interval range for the true mean of the post-treatment cores was 45 to 98 ppm. Table 1 presents a summary of these results. The most dominant chemical species were consistently chlorobenzene, trichloroethene, and tetrachloroethene. Percent removal in individual blocks in the 12-block test area varied from 54% to 96% with an average value of 85%. Similar results have been obtained in tests conducted throughout the Annex Terminal site by TTUSA. Baseline Testing of 10 blocks in Areas A, B, and D demonstrated an average post-treatment volatile contaminant concentration of 61 ppm. Average pre-treatment concentration of volatile contaminants in these blocks was 2,140 ppm.

In the 6-block test area, the final volatile contamination within a block was reduced to an average level ranging from 16 to 119 ppm (based on the analyses of composite cores). The average for the entire 6-block test area was 53 ppm total volatile organics with a standard deviation of 73 ppm. The 95% confidence interval range for the true mean of the post-treatment cores was 19 to 87 ppm. These results are also summarized in Table 1. Ketones (specifically acetone, 2-methyl-4-pentanone, and 2-butanone) were found to be the primary contaminants in the post-treatment soil. Percent removal data could not be calculated for treatment in this area since pre-treatment data was only available for one discrete depth of one core obtained from the 6-block test area. The purpose of this additional testing was not to determine process efficiency, but only to evaluate contaminant concentration after treatment.

While the percent removal for VOCs is impressive, the important evaluation criterion here is not so much the amount of contamination removed, as it is the level to which the contamination is reduced. TTUSA's operational objective was to obtain a final contamination level in the soil of 100 ppm or less. The post-treatment contamination level appears to be a function of the treatment time. The longer a block is treated, the lower the final contamination level for that particular block.

A significant finding from the second phase of post-treatment sampling (in the 12-block test area) during the Demonstration Test was that, one in every 6 sampled cores (composite or discrete) still showed levels of contamination above the 100 ppm target level. This finding had not been identified during previous testing and is discussed in more detail in the Technology Evaluation Report. Discrete samples from blocks A-31-e and A-35-e both show that the lower portion of the block appears to be less well treated. However, this may be due to the manner in which the stripper was operated, i.e., the augers may have passed below the maximum treatment depth (5 feet in the 12-block test area) and brought up contamination from below the treated area without allowing sufficient time for treatment of this contaminated soil. If this was the case, then generation of a buffer zone or treatment to below all zones of contamination would eliminate this problem.

To further investigate this theory, phase three post-treatment sampling of the Demonstration Test was conducted in the 6-block test area where the soil was treated to below the full zone of contamination. Here, one in every 9 soil cores obtained from this sampling effort demonstrated post-treatment contamination levels above 100 ppm. This is not statistically different from the 1 in 6 cores above 100 ppm in the

Table 1. **Demonstration Test Results for Volatiles**

12-Block Test Area

Block Number	Pre-Treatment (μg/g)	Post-Treatment (μg/g)	Percent Removal (%)
A-25-e	54	14	73
A-26-e	28	12	56
A-27-e	642	29	96
A-28-e	444	34	92
A-29-e	850	82	90
A-30-e	421	145	65
A-31-e	788 [a]	61	92
A-32-e	479	64	87
A-33-e	1133	104	91
A-34-e	431	196	54
A-35-e	283	60	79
A-36-e	153	56	64
Avg[b]	466	71	85
Std Dev[b]	457	80	NA[c]

6-Block Test Area

Block Number	Pre-Treatment (μg/g)	Post-Treatment (μg/g)	Percent Removal (%)
A-26-n	NA	16	NA
A-27-n	NA	22	NA
A-28-n	NA	36	NA
A-29-n	NA	80	NA
A-30-n	NA	119	NA
A-31-n	NA	45	NA
Avg[b]	NA	53	NA
Std Dev[b]	NA	73	NA

[a] Only analyses of 2 of the 3 sample cores taken were available.
[b] Reported for the entire treatment area based on analysis of all composite cores.
[c] Not applicable.

12-block test area. Therefore, these data do not fully support the idea that residual contamination above 100 ppm was due to bringing untreated soil into the treated area. Untreated soil below the maximum treatment depth in the 6-block test area did not show signs of contamination.

Although a direct comparison cannot be made between the performance of the *in situ* steam/hot-air stripper in the 12-block test area and the 6-block test area, intuitively the stripper seems to have performed better in the 6-block test area. The initial levels of contamination appeared to be higher based on in-line monitoring equipment and the soil had a higher clay content. Also, volatile contamination in the 6-block test area was primarily ketones with no significant concentrations of the contaminants detected in the 12-block test area (i.e., chlorobenzene, trichloroethene, and tetrachloroethene). Ketones may be more difficult to remove because of their increased water solubility.

During TTUSA's Baseline Calibration test, TTUSA developed a correlation between the in-line monitoring equipment [a flame ionization detector (FID) and a gas chromatograph (GC)] which measure VOC concentrations in the shroud and the actual VOC contamination in the soil. This correlation provides a contamination profile during operation; it also acts as an indicator to determine the termination point for treatment of a particular block. TTUSA's operational objective is to attain less than 100 ppm total VOCs in each block treated. The results of TTUSA's Baseline Testing; Process Improvement and Soil Vapor Emissions Tests; and Mixing, Treatment, and Downward Migration Tests (see Appendix D), however, show that VOC contamination levels in only 75% of the 16 blocks tested (in Areas A, B, and D) were reduced to below 100 ppm. The Demonstration Test was conducted entirely in Area A. Volatile organic contamination levels in 75% of the blocks in the 12-block test area and 83% of the blocks in the 6-block test area sampled during the Demonstration Test were reduced below this target level based on averaging the three composite cores obtained from each block. All previous sampling by TTUSA in Area A had indicated that the technology had reduced the VOC level to below the desired 100 ppm in 100% of the blocks sampled. In their testing, however, TTUSA determined the final treatment level by taking two discrete samples from one core within the treated block. These discrete samples were taken at depths of 2.5 and 4.5 feet. The sampling and analysis performed during the Demonstration Test was much more extensive than had been previously accomplished. It is possible that the TTUSA sampling strategy was not comprehensive enough to find local zones of high contamination after treatment of the block.

The failure of the process to reduce VOC contamination to the target level in some of the test blocks is likely related to a deficiency in the FID-GC/soil contamination correlation, not the technology itself. This correlation estimates the actual soil contamination based on FID readings which are verified by GC readings. Both the FID and GC give an average reading of the level of organic compounds in the shroud. "Hot spots" in the soil within the treated block are not identified by either of these instruments. There is potential for error in both the initial generation of the correlation and the actual practice of utilizing it. The technology has technically demonstrated the ability to reduce contamination in soil to very low levels. The residual contamination levels above 100 ppm encountered in some treatment blocks may be attributed to operational, not technical, factors. All of the blocks in the Demonstration Test that had an average contamination level greater than 100 ppm after treatment had final FID readings that were relatively high. It appears that, to achieve a low cleanup level without any "hot spots", the average FID attained on the final pass should be as low as possible with respect to the target treatment level. Failure to reduce the shroud FID reading throughout the entire treatment block can lead to incomplete treatment in portions of the block. This requirement obviously conflicts with the economics of the process since site cleanup becomes more expensive as treatment time per block increases.

Semivolatile contamination in the 12-block test area prior to treatment was high, ranging from 336 up to 1,400 ppm total SVCs. Post-treatment contamination was reduced to levels as low as 49 ppm and as high as 818 ppm total SVCs. As previously mentioned, however, the fate of these semivolatiles has not been determined. The major semivolatile contaminants found in the soil during the Demonstration Test were bis(2-ethylhexyl)phthalate and phenols. Levels of semivolatile contaminants were reduced on average by over 50%. This is comparable to other studies conducted on SVCs: the Bench-Scale Tests indicated levels of SVCs reduced ranged from approximately 45% to 85%; reduced levels of SVCs calculated during the Baseline Testing were 65% to 95%. The higher percent removals of SVCs obtained during independent TTUSA testing is a result of higher initial concentrations. Appendix D, "Case Studies", describes the results of these tests.

Poor SVC mass balances encountered throughout testing activities raised questions regarding the fate of semivolatiles as a result of treatment. The Bench-Scale Tests (see Appendix D) were performed in part to address this issue. Although several theories have been investigated, none provide any supporting data. One possible explanation for the poor semivolatile mass balances is that a reaction of the phthalate compounds, catalyzed by the clay in the soil, is taking place. The expected result of such reactions would be phthalate salts, which are chemically bound to the soil, and alcohols, which would decompose and dehydrate to form C8 - C15 aliphatic hydrocarbons. However, analysis of post-treatment samples does not indicate the presence of these compounds. The probability that the SVCs may have migrated down below the treatment block by the flushing action of condensing steam from the treatment process was also investigated during the Demonstration Test. Qualitative fluorescein dye testing indicated that downward migration of the dye did not appear to be a result of treatment which confirmed earlier testing by TTUSA (see Mixing, Treatment, and Downward Migration Tests, Appendix D).

The SVC reduction percentages reported for the Bench-Scale Tests (45% to 85%), obtained in a contained system, are comparable to results obtained during full-scale testing. Large amounts of SVCs were still unaccounted for in the contained system tests. The results of the Bench-Scale Tests suggest that downward migration, biological activity, and dilution by mixing are not significant factors in the field treatment results.

The 1240 L of condensed organics collected in the holding tank during treatment of the 12-block test area separated into two distinct phases. The top phase was clear and colorless with a density of 0.997 g/mL. This phase consisted primarily of water with only about 1% organic contamination. The bottom phase was yellowish in color and slightly opaque with a density of 1.192 g/mL. This phase was over 90% condensed organics, mostly volatiles. The volume of the top phase was more than twice that of the bottom phase. This was typical of normal operational conditions. The volume of the upper phase (mostly water) can easily be reduced by recycling the top phase liquid through the distillation system. The distillation system removes the majority of the water and directs it to the cooling tower; the remaining condensed organics are again directed to the holding tank to await disposal. Chlorobenzene,

trichloroethene, and tetrachloroethene dominated the chemical composition of the condensed organics collected during the treatment of the 12-block test area. This was anticipated since these three volatile compounds were the major soil contaminants.

Prior to passing through the wet carbon bed after the distillation process, the average volatile contamination level in the water stream during treatment of the 12-block test area was approximately 280 ppm; semivolatile contamination averaged approximately 140 ppm. The water stream showed significant reductions in contamination levels after passing through the wet carbon bed. The levels decreased by an average of 97% for volatile contaminants and 99% for semivolatiles. Residual VOC levels averaged near 8 ppm; residual semivolatile organic compound levels averaged less than 55 ppb. The carbon bed thus removes significant amounts of contaminants from the water stream and reduces the final concentration of contaminants in this stream to a satisfactory degree. Residual contamination in the treated water is released as an air emission, not a water discharge. The impact of residual contamination is somewhat diminished by the dilution effect of the treated water stream upon entering the cooling tower sump. Organic vapor analyzer (OVA) readings taken during the Demonstration Test of the exhaust plume of the evaporative cooling tower did not detect any volatilization of organic compounds in the tower sump.

The *in situ* steam/hot-air stripper operates as a closed process except when one of the dry activated carbon beds is undergoing regeneration. The only potential escape path for contaminants leaving the system is in the air discharged from the inactive carbon bed stack during bed regeneration. Typical levels of contamination in this recycled stream were low (<50 ppmV) although sampling activities indicated one high level (approximately 500 ppmV). This high value was most likely obtained just prior to breakthrough of the activated carbon bed before regeneration. The return airstream from the active carbon bed is recycled back to the ground through the augers. Any contaminants in this airstream are reinjected into the soil and are again subjected to the treatment process.

Certain chemical species are more difficult to remove from the soil by *in situ* steam/hot-air stripping than others. High boiling point VOCs require longer block treatment times than compounds with lower boiling points. This is expected based on the simple relation between boiling point and volatilization. Baseline Testing (see Appendix D) indicated that those compounds with boiling points below 175°F (80°C) were frequently removed to levels which could not be detected. When they were detected, these low boiling compounds exhibited significant reductions in concentrations. Those with boiling points above 175°F also exhibited significant reductions in concentration, but the concentrations were less frequently reduced to below the detection limit. Testing operations have indicated that tetrachloroethene is a particularly difficult compound to remove. The difficulties encountered in removing tetrachloroethene can be explained by its known high stability and resistance to hydrolysis. Further information may be found in TTUSA's Baseline Testing; Process Improvement and Soil Vapor Emissions Tests; and Mixing, Treatment, and Downward Migration Tests (Appendix D). Xylenes are typically difficult compounds to remove

because of their high molecular weight. However, bench-scale testing of steam stripping processes have shown that xylenes can be removed by this type of process [1].

Using data generated during the Demonstration Test, mass balances were attempted on both the condensed organics and the water. The organic mass balance could not be performed. When the pre- and post-treatment soil contamination levels were compared to the amount of organics collected in the condensed organics tank, it was found that a large discrepancy occurred. This discrepancy could easily occur because of the highly heterogeneous nature of the soil prior to, and even after, treatment. The wide standard deviation around the mean of the pre-treatment composite cores indicates the difficulty in accurately characterizing the heterogeneous blocks and accounts for the poor closure obtained. The discrete core samples and the dye samples also show inhomogeneity in the post-treatment soil blocks. Holdup of contaminants in the process system before the Demonstration Test could also introduce error into the balance. The water balance achieved a more satisfactory result with approximately 50% of the water being accounted for in the soil or the treatment process. The high standard deviation in the pre- and post-treatment percent moisture analysis in the soil samples and suspected inaccuracies in the ability to measure totalized volumes in all of the water streams account for complete lack of closure in the balance.

Although *in situ* treatments are not subject to land ban regulations, toxic characteristic leaching procedure (TCLP) was performed on soil samples before and after treatment. These analyses indicated that the treatment process has little effect on the leachability of the soil. However, they also showed the heterogeneous nature of the treatment blocks before and after treatment. The leachability of the contaminants in all post-treatment soil samples were below the regulatory limits as listed in the *Federal Register* [2].

Operational Test Results

Semivolatile compounds that were unaccounted for following treatment prompted investigation into the potential of the process to induce downward migration of contaminants. A dye study which utilized fluorescein dye packets to trace the behavior of the contaminants during treatment was conducted as part of the Demonstration Test. Four blocks in the 12-block test area were spiked with fluorescein dye before treatment began in the test area. Following treatment by the TTUSA process, these blocks were sampled within and below the treatment area and analyzed for the presence of the dye. A similar study was conducted by TTUSA in their Mixing, Treatment, and Downward Migration Tests (see Appendix D). Both tests indicated that downward migration of organic contaminants to below the zone of treatment did not appear to be a result of treatment. Dye was found to be present in samples taken below the treatment depth but at concentrations significantly lower than within the treatment area. Occasionally, high levels of fluorescein were found at a particular depth (sample interface) below the zone of treatment. In these instances, it was assumed the dye at this location could be due to cross-contamination of samples. Because the fluorescein dye is more soluble than the VOCs or SVCs found on-site, it is reasonable to assume that any downward migration of the VOCs and SVCs is less than that displayed by the dye.

Fugitive emissions from both the soil and the process itself were sampled and monitored during and after treatment. Fugitive emissions from the soil were low, on the order of approximately 21 grams for total emissions due to treatment of a single block (based on data gathered from the 12-block test area). Some heating of the soil surrounding a block undergoing treatment occurs during its treatment. The effect of this heating on fugitive emissions was evaluated during the Demonstration Test by placing flux chambers on four blocks surrounding the treated block (see Figure 1) and on the treated block itself after treatment was completed and the shroud had been removed. During treatment of the Demonstration Test block, Location 1 had the lowest emission rate of the five locations sampled. Location 1 lies in a row which had already undergone treatment. The majority of the contamination had been removed by treatment, and sufficient time had elapsed to allow the emission rate to reach background levels. Treatment in Location 1 was also responsible for driving out a portion of the contamination from Location 2. Emission rates from Location 2 (untreated) were therefore higher than those from Location 1 (treated) but lower than those from Locations 4 and 5 (also untreated). Location 4 demonstrated the highest emission rate for samples taken during treatment of the highlighted block in the configuration shown in Figure 1. This result is reasonable since Location 4 lies in an untreated area adjacent to the block currently undergoing treatment. In addition, it is not adjacent to any other blocks that have already been treated, eliminating the possibility for any contamination to be driven off by treatment of these blocks.

Although the emission rate from Location 4 was the highest among those sampled in the configuration shown in Figure 1, it was substantially lower than that observed from the previously treated adjacent block immediately following its treatment. The emissions from this block were high immediately upon completion of its treatment, but decreased rapidly with time. The emissions were expected to be relatively high since the block, still hot from its treatment, was no longer covered by the shroud and off-gases were allowed to escape from the soil into the atmosphere. Operational testing by TTUSA during their Process Improvement and Soil Vapor Emissions Tests (see Appendix D) demonstrated that using a 2-inch layer of clean soil to cover treated treatment blocks reduces fugitive emissions by over 50%. This procedure has since been put into practice and the primary source of fugitive emissions has been reduced. Since emission rates are so low, testing has not been performed to evaluate the effect of covering the treated blocks with a deeper layer of clean soil (greater than 2 inches), but it is anticipated that use of a deeper layer of clean soil would result in greater reductions in the emission rates. Overall, the fugitive emissions generated from treatment of a block are considered to be insignificant.

Potential process fugitive emissions were also monitored during operation of the *in situ* steam/hot-air stripper to ensure that contaminants were not leaking into the atmosphere. Potential gas leakage from the shroud, exhaust from operation and steam regeneration of the gas-phase carbon beds, and cooling tower evaporative vapors were also periodically monitored with an OVA instrument.
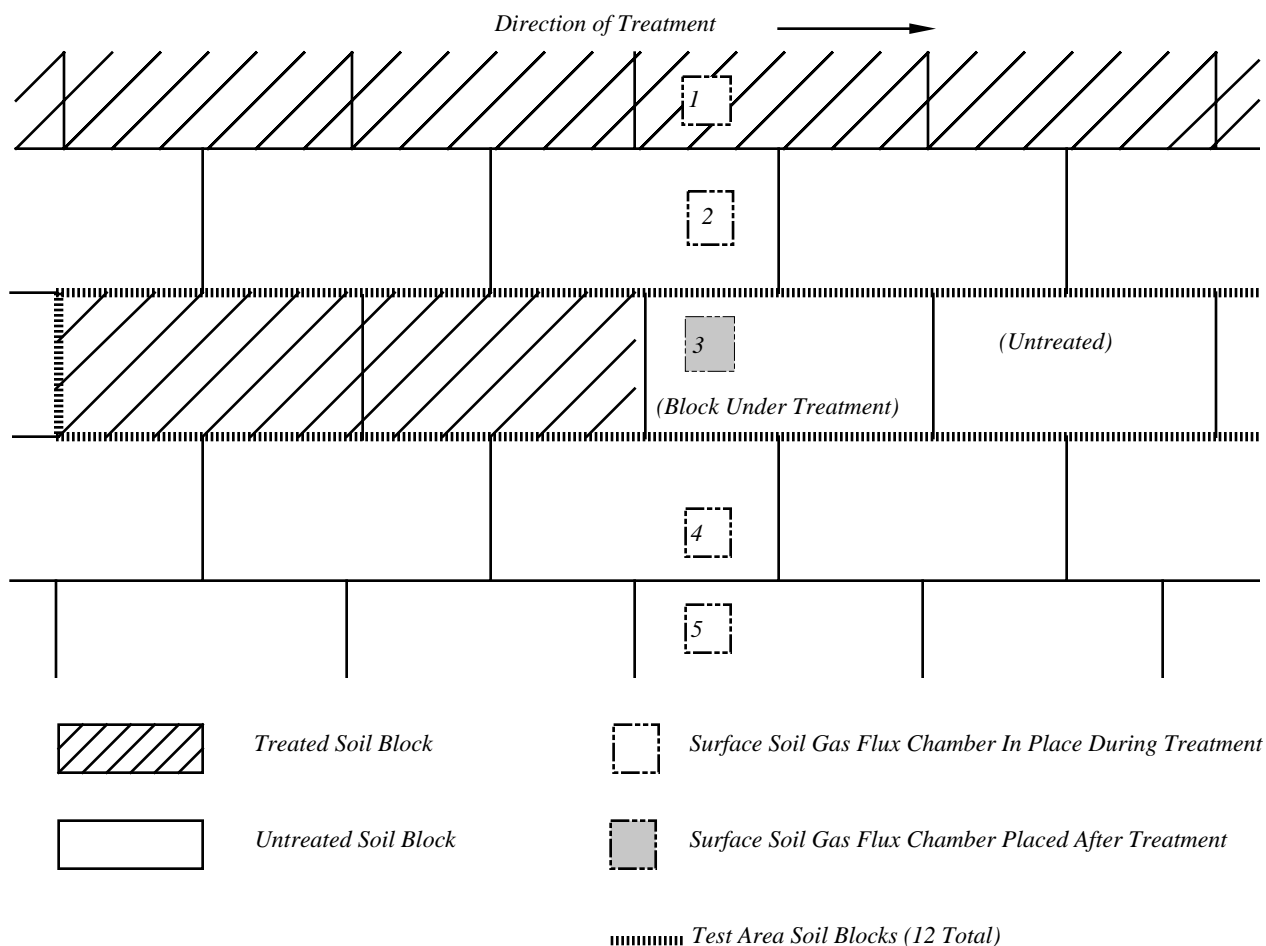
9

Figure 1.   *Sampling locations for fugitive emissions.*

Apart from emissions produced by regeneration of the carbon beds, process emissions during the Demonstration Test were low. Research performed since the completion of the Demonstration Test revealed that the path between the two carbon beds was inappropriately closed off by flapper valves. This situation has since been rectified by replacing the flapper valves with butterfly valves equipped with viton seats.

Based on information provided by TTUSA, soil type has an effect on the rate of treatment. Clay soils are generally the most difficult to treat. Organic compounds have a greater tendency to bind to clay soils due to the structure and organic content of the clay soils. Volatilization of organic compounds in the soil is therefore more difficult to achieve. Clay soils also offer slightly more resistance to penetration and mixing by the augers than other soil types, contributing somewhat to their treatment demand. Sandy soils demonstrate much shorter treatment times than clay soils.

An on-line treatment time factor of 71% was achieved during the Demonstration Test. This was determined by comparing the operation time to the time spent on-site each workday. The operation time excludes downtime for maintenance (as this is performed during separate shift hours) but includes time required for relocation of the shroud since this is part of normal operating procedures. Downtime experienced

in a normal workday is attributed to operational maintenance to remedy clogged nozzles, freezing problems in the refrigeration system, loss of vacuum beneath the shroud, etc. TTUSA claims an on-line factor of 70% to 75% can be attained during normal operation of the *in situ* steam/hot-air stripper.

The chemical profile of the contaminants in the soil affects the treatment rate. A site contaminated with very volatile compounds, such as gasoline, can be treated rapidly. High concentrations of volatile contaminants or the presence of semivolatile contaminants would require longer treatment times for each block. As mentioned previously, certain chemical species can also demand more remedial attention.

The mixing action of the augers does not produce a homogeneous area of treatment. The augers and cutter bits were designed to loosen and homogenize the soil in their vicinity while injecting steam and hot air to volatilize contaminants. Based on test results, homogeneous mixing is not an apparent consequence of auger action. Residual contamination in the treated blocks was anticipated to be fairly homogeneous. Instead, treated soil blocks are extremely heterogeneous in nature as indicated by chemical analyses for volatile and semivolatile contaminants and dye test data. Wide vertical and lateral variation is exhibited among post-treatment samples obtained from the same block.

The technology is a mobile process transportable from site to site. The unit can be conveyed on five tractor/trailer rigs, one of which is designated an oversize/overweight load. Assembly of the steam/hot-air stripper can be performed in one week. Disassembly of the equipment also requires one week.

The extent of post-treatment requirements is dependent on the future use of the site. The site is left clear and free of subsurface objects. This may or may not be beneficial since all sewer piping and underground wiring is removed prior to treatment and therefore these utilities must be replaced. Treatment of the soil utilizing this stripping process also leaves the soil disturbed so that it is no longer compacted or level. The treated areas may require grading and recompaction based on the anticipated service of the site.

Physical Test Results

Results from the Demonstration Test do not indicate a significant statistical change in the moisture content of individual soil blocks as a result of treatment. Evaluation of the average moisture content for the entire 12-block test area did, however, show a slight decrease in the moisture content as a result of treatment with average pre-treatment levels of approximately 30% and average post-treatment levels of approximately 28%. Baseline Testing (see Appendix D) in three areas also indicated a slight decrease in average moisture content from pre-to post-treatment. The data are not statistically conclusive because of the high standard deviation.

The bulk density of individual blocks appears to increase slightly as a result of treatment based on Demonstration Test and Baseline Testing results. The average bulk density of all blocks in the 12-block test area of the Demonstration Test increased from 1.52 g/cc to 1.55 g/cc following treatment. Again, the high standard deviation of the data leads to inconclusive results.

The specific gravity of the soil increased by an average of 6.5% in the 12-block test area evaluated during the Demonstration Test. Analysis of this property provides a measure of the void space in the soil and indicates that the porosity decreased.

Ranges of Site Characteristics Suitable for the Technology

Site Selection

The selection of sites with potential for treatment by the *in situ* steam/hot-air stripping technology is based on the following criteria:

- Only soils contaminated with volatile organics are potentially remediable by this particular technology.

- The site ideally requires sufficient land area around the identified treatment area to provide a buffer zone to maneuver the *in situ* steam/hot-air stripping unit. Sufficient uncontaminated space adjacent to the treatment area is also required for placement of support equipment and trailers.

- Access roads must be available and must be able to convey the trailer transporting the control room and cat-

erpillar, which is classified as an overwidth load and weighs approximately 88,000 pounds.

- A minimum treatment area of approximately 0.5 acres (20,000 square feet) is necessary for economical utilization of the *in situ* treatment technology.

Surface, Subsurface, and Clearance Characteristics

The rig can apply a pressure of up to 25 pounds per square inch (psi) on the underlying soil when the shroud is lifted. Therefore, the area to be treated by the *in situ* stripper must be capable of supporting the treatment rig so that it does not sink or tip. The soil must be penetrable by the augers and free of underground piping, wiring, tanks, or drums. Materials of this type must be relocated before treatment can commence. Surface and subsurface obstacles greater than 12 inches in diameter including rocks, concrete, and trash metal must be removed to avoid damage to the stripping equipment. Incomplete treatment could result if these materials are not removed. Sites with large known or suspected amounts of such material may be unsuitable for *in situ* treatment due to the effort required for removal.

Power and telephone lines or other overhead obstacles must be removed or rerouted to avoid conflict with the 30-foot treatment tower.

Topographical Characteristics

The ground where treatment will be performed must be flat and level. For the current *in situ* steam/hot-air stripper model the surface must be gradeable to less than 1%.

Site Area Requirements

The site requires sufficient space for a bermed equipment decontamination area, a small personnel decontamination area, two or more liquid storage tanks, and office trailers. The treatment area should meet the minimum area requirements for economical use of the *in situ* steam/hot-air stripping unit.

The shape of the site is also important; rectangular areas are most efficient. A site which is broken up into oddly-shaped or narrow areas by buildings or natural formations may provide an extra challenge to the maneuverability of the equipment, require additional treatment time per soil treatment block, and result in less efficient block treatment patterns.

Climate Characteristics

Since the steam/hot-air stripper operates on the soil *in situ*, any climatic conditions that affect properties of the soil adversely with respect to the treatment process may render the site inappropriate for treatment by this process. For example, an extremely cold climate, where the soil becomes frozen solid, would cause difficulty with soil penetration and would require large amounts of energy to heat the soil to the treatment temperature; the same is true of snow covered ground.

Cold temperatures would increase heat loss from the equipment, requiring additional heat input to the steam and hot air, while aiding the efficiency of the condensing coolers. Although the equipment's operational abilities in very cold temperatures have not been fully determined, the most likely

limiting factor is the diesel fuel lines, which would begin to experience flow problems at ambient temperatures less than 20°F. Freezing of cooling water lines may also limit the operating temperature for the stripper. Thorough insulation of all lines may allow for operation in even colder weather.

Hot weather (high ambient temperature) decreases the cooling capacity of the evaporative cooling tower. This, in turn, reduces the effectiveness of the water coolers in condensing organics in the treatment train. The upper temperature limit for effective operation is an ambient temperature of approximately 100°F. Problems caused by hot weather may be alleviated by operating the *in situ* steam/hot-air stripper at night, if ambient nighttime temperatures allow. In general, moderate temperatures are preferred for optimal operation.

Saturated surface soils, especially those with high clay content, may impede the movement of heavy equipment and may not be capable of supporting the unit's weight. Therefore, although heavy annual rainfall does not preclude the use of the *in situ* steam/hot-air stripping technology, scheduling operations during the drier seasons may result in more efficient and timely treatment.

Severe storms may result in hazardous operating conditions, since the equipment is fully exposed to the weather. The process tower, often standing alone or standing taller than surrounding structures, provides a ready pathway for lightning.

Geological Characteristics

Major geological constraints that can render a site unsuitable for *in situ* steam/hot-air treatment include landslide potential, volcanic activity, and fragile geological formations that may be disturbed by heavy loads or vibrational stress.

The entire treatment area must be composed exclusively of soil, at least to the proposed treatment depth. Unremovable rock formations in the treatment area would preclude use of the *in situ* stripper. Although the *in situ* steam/hot-air stripper is capable of treating most kinds of soil, the soil type impacts treatment process time and effectiveness. Soil type also dictates acceptable climate characteristics by its response to rainfall and other climatic conditions. Wet sandy soils tend to have a greater load capacity than other wet soils. Soils with more clay and silt tend to become malleable and unstable when wet, potentially causing problems with the support and mobility of the equipment. Dry, clay soil can form hard clumps which may not break up during the treatment process, thus reducing the effectiveness of treatment. Also, data from the Baseline Calibration (see Appendix D) suggests that organic contaminants may bind more strongly with clay soils than to soils with larger particles.

The presence of a shallow water table does not preclude treatment with the *in situ* steam/hot-air stripper. The unit can easily and efficiently treat the soil and water in and below the saturation zone as a normal part of site treatment. This result was not identified during the Demonstration Tests, but has been demonstrated by TTUSA in operations following the completion of the demonstration.

Utility Requirements

The *in situ* steam/hot-air stripping process requires water supply of at least 8 to 10 gallons per minute (gpm) at 30 pounds per square inch gauge (psig). Power for the *in situ* steam/hot-air stripper is provided by on-board diesel generators.

Environmental Regulations and Comparison with TTUSA Stripping Technology Performance

Operation of the TTUSA *in situ* steam/hot-air stripping technology for treatment of contaminated soil will require compliance with certain Federal, State, and local regulatory standards and guidelines. This technology may be used at Federal Superfund National Priorities List (NPL) sites and other sites. Superfund site regulatory requirements applicable to the use of this technology are discussed below under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Other Federal, and State and local environmental regulations are subsequently discussed in more detail as they apply to the performance, emissions and residuals evaluated from measurements taken during the Demonstration Test.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 as amended by the Superfund Amendments and Reauthorization Act (SARA) of 1986 provides for Federal funding to respond to releases of hazardous substances to air, water, and land. Section 121 of SARA, entitled Cleanup Standards, states a strong statutory preference for remedies that are highly reliable and provide long-term protection. It strongly recommends that remedial actions use on-site treatment that "...permanently and significantly reduces the volume, toxicity, or mobility of hazardous substances." In addition, general factors which must be addressed by CERCLA remedial actions are:

- long-term effectiveness and permanence;
- short-term effectiveness;
- implementability; and
- cost.

The TTUSA *in situ* steam/hot-air stripping technology has been shown to remove an average of approximately 85% of VOCs from contaminated soil at the demonstration site. In this respect, the technology "permanently and significantly" reduces the volume, toxicity, and potential mobility of the contaminants in the soil.

The use of this technology for site treatment results in a certain degree of long-term effectiveness and permanence because hazardous wastes are actually removed from the soil during treatment. Over the short term the potential for human exposure to contaminated soil from excavation or contact with surface soil is immediately and significantly reduced after treating the site. Exposure due to excavation is minimal since this is an *in situ* process. Fugitive air emissions from the soil and from the process during operation of the stripping technology have been determined to be low. These results are further discussed below under "State and Local Regulations."

In addition to the above general requirements, Section 121 of CERCLA requires that Superfund treatment actions must meet or exceed any "applicable or relevant and appropriate" (ARAR) standard, requirement, criteria, or limitation under any Federal law or State environmental statute. Local standards may also be relevant and appropriate. These criteria, as related to use of the TTUSA stripping technology, are discussed below.

Federal Regulations

Resource Conservation and Recovery Act (RCRA)

The Resource Conservation and Recovery Act (RCRA) is the primary Federal legislation governing hazardous waste activities. Subtitle "C" of RCRA contains requirements for generation, transport, treatment, storage, and disposal of hazardous waste, most of which are also applicable to CERCLA activities.

The primary hazardous waste generated by the TTUSA process is the condensed organics removed from the contaminated soil. Due to generation of this hazardous waste, the site responsible party must obtain a EPA generator identification number and comply with accumulation and storage requirements for generators under Title 40, Code of Federal Regulations (CFR), Part 262 (July 1, 1988) or have a Part B, Treatment, Storage, and Disposal (TSD) permit or interim status. (Compliance with RCRA TSD requirements is required for CERCLA sites.) A hazardous waste manifest must accompany off-site shipment of waste. Transport must comply with Federal Department of Transportation (DOT) hazardous waste transportation regulations. The receiving TSD facility must be permitted and in compliance with RCRA standards.

The RCRA land disposal restrictions (40 CFR Part 268) require that certain hazardous wastes receive treatment after removal from a contaminated site and prior to land disposal, unless a variance is granted. Since the condensed organics are a liquid hazardous waste, treatment will be required prior to land disposal. Technology or treatment standards have been established for many liquid hazardous wastes; those applicable to use of the TTUSA process at a given site will be determined by the type of waste generated. Incineration of this liquid hazardous waste may be the Best Demonstrated Available Treatment (BDAT) prior to disposal (of any residue) in a certified landfill.

Another disposal option for the waste which is classified as recycling under 40 CFR Parts 261 and 266, may be burning the waste in a boiler or an industrial furnace such as a cement kiln. However, a waste must meet BTU requirements of 5,000 to 8,000 BTU to be treated in this manner [3]. State regulations may further restrict the wastes and appropriate treatment techniques.

Soil treatment by the stripping technology is an *in situ* process and therefore the soil itself does not require land disposal and compliance with the associated land disposal restrictions.

Clean Water Act

The Clean Water Act (CWA) regulates direct discharges to surface water through the National Pollutant Discharge Elimination System (NPDES) regulations. These regulations require point-source discharges of wastewater to meet established water quality standards. The TTUSA process has a cooling water blowdown discharge and a boiler blowdown discharge. These wastewaters are anticipated to be discharged to the sanitary sewer, requiring a discharge permit or at least concurrence from state and local regulatory authorities that the wastewater is in compliance with discharge standards. The cooling water blowdown may contain residual VOCs from the water purification process. Although not classified as a hazardous waste, this wastewater may require treatment for removal of VOCs (specifically, chlorinated organics) prior to sewer discharge.

Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) establishes primary and secondary national drinking water standards. These standards consist of Maximum Contaminant Levels (MCLs), MCL Goals (MCLGs), and aesthetic standards. MCLs are relevant and appropriate as *in situ* cleanup standards where either surface or groundwater is or may be used for drinking water. Although the TTUSA technology is designed and intended for treatment of contaminated soils, residual soil contamination after treatment could potentially impact groundwater quality through leaching. Therefore, the use of MCLs for VOCs of concern may be relevant and appropriate at sites overlying a drinkable groundwater aquifer.

Clean Air Act

The Clean Air Act (CAA) establishes primary and secondary ambient air quality standards for protection of public health, and emission limitations for certain hazardous air pollutants, including benzene. The pollutants listed in the ambient air quality standards are generally not applicable to operation of the TTUSA *in situ* steam/hot-air stripping technology, except perhaps for diesel exhaust, which may be more stringently regulated by state or local standards. The emission standards for hazardous air pollutants promulgated thus far have been rather narrowly defined; they apply only to new and modified stationary sources, and will probably not be relevant to TTUSA technology treatment activities.

The Federal environmental regulations discussed above are the most significant for operation of the TTUSA stripping technology. However, other statutes may have ARAR requirements. Some of these ARARs may be location- and action-specific.

State and Local Regulations

Compliance with ARARs may require meeting State standards that are more stringent than Federal standards or may be the controlling standards in the case of non-CERCLA treatment activities. For use of the TTUSA stripping technology, soil cleanup standards will be the most significant of these standards. These standards may be based on the results of a waste site risk assessment. Results from the Demonstration Test showed that the overall average post-treatment soil VOC contamination was 71 ppm with a standard deviation of 80 ppm. The 95% confidence interval range for the true mean

of the post-treatment cores was 45 to 98 ppm. Mean residual soil VOC levels ranged from 12 to 196 ppm. Results of Baseline Testing by TTUSA in September 1988 (see Appendix D, "Case Studies") showed that mean residual VOC levels ranged from 12 to 140 ppm.

Air emissions may also be regulated by the State and/or local air quality district. These may include exhaust emissions from the stripping technology's diesel engines, emissions from contaminated soil excavation activities, and releases of reactive organic gases, such as some of the volatile compounds treated by the TTUSA technology. Based on the Demonstration Test results and assuming that six heavily contaminated soil blocks are treated each day, the total emissions from the blocks would be less than 140 g/day (about 0.3 lb/day). The maximum limitation by the SCAQMD for release of reactive organic gases is 34 kg/day (75 lb/day).

Water quality may also be regulated by State standards. The State water authority could specify standards for groundwater beneath the site or for potentially contaminated surface water runoff. The TTUSA process has successfully treated contaminated soil in and below the water table. Groundwater quality may potentially be directly affected by treatment into and below the water table. Preliminary data indicates that the groundwater itself is actually treated.

Section 4
Economic Analysis

Introduction

The primary purpose of this economic analysis is to estimate costs (not including profits) for a commercial-size treatment utilizing the transportable TTUSA *in situ* steam/hot-air stripping system. The costs associated with this technology are defined by 12 cost categories that reflect typical cleanup activities encountered on Superfund sites. Each of these cleanup activities is defined and discussed, forming the basis for the estimated cost analysis presented in Table 2. The costs presented are based on treatment of 8,925 yd^3 of contaminated soil, the amount of soil to be treated at the Demonstration Test site.

The actual Demonstration Test treated approximately 65 yd^3 of contaminated soil at the site. The costs presented in Table 2 are based on anticipated on-line operations of the unit since periodic shutdowns are required in order to respond to maintenance or operational problems. Costs are given for 70%, 80%, and 90% on-line conditions. Costs which are assumed to be the obligation of the responsible party or site owner have been omitted from this cost estimate and are indicated by a line (—) on Table 2. Categories with no costs associated with this technology are indicated by a zero (0) on Table 2.

Important assumptions regarding operating conditions and task responsibilities that could significantly affect the cost estimate results are presented below:

- The cost estimates presented in this analysis are representative of charges typically assessed to the client by the vendor and do not include profit. Costs such as preliminary site preparation, permits and regulatory requirements, initiation of monitoring programs, waste disposal, sampling and analyses, and site cleanup and restoration are considered to be the responsible party's (or site owner's) obligation and are not included in the estimate presented. Whenever possible, applicable information is provided on these topics so that the reader may perform his own calculations to obtain relevant economic data.

- The treatment area is divided into 1,643 blocks each measuring 7 ft-4 in by 4 ft and treated to a depth of 5 ft. The total volume of each block is 5.43 yd^3, and the total volume treated is 8,925 yd^3.

- For hypothetical 100% on-line conditions, the treatment rate is assumed to be 3 cubic yards per hour. Operations are assumed to be 16 hours a day, five days a week with the exception of site preparation operations that are assumed to be 8 hours a day, five days a week.

- Operations for a typical 16-hr day require: one supervisor, two health and safety engineers, four operators, and five mechanics.

- Site preparation estimates do not include administrative costs; these administrative costs are included in estimates for assembly, treatment, and disassembly.

- Equipment capital costs are not used directly and are limited to the cost of the *in situ* steam/hot-air stripper ($1,981,000). Percentages of this $1,981,000 are used for estimating purposes.

- Depreciation and other costs that are estimated as percentages of equipment capital costs on an annual basis have been prorated. (The costs for depreciation and insurance and taxes accrue during assembly, treatment, and disassembly; scheduled maintenance costs accrue during treatment only; contingency costs are assessed for the entire length of the project including site preparation, assembly, treatment, and disassembly.)

- A 65% utilization factor is incorporated into depreciation costs to account for depreciation that occurs during maintenance, marketing, and regulatory delays which take place while the equipment is not on-site.

- Wastewater is assumed to meet local water quality standards.

Many actual or potential costs that exist were not included as part of this estimate. They were omitted because site-specific engineering designs, that are beyond the scope of this SITE project, would be required. Certain functions were assumed to be the obligation of the responsible party or site owner and were not included in the estimates.

Results of Economic Analysis

Table 2 presents the economic analysis for operating factors ranging from 70% and 266 treatment days (399 days on-site) to 90% and 207 treatment days (315 days on-site). Data gathered during the Demonstration Test indicates that a 70% on-line factor most closely represents the operating conditions during this period of time. The results of the analysis show a cost per cubic yard range from $252 to $317.

15

Table 2. Estimated Costs in \$/Cubic Yard[a,b]

	On-line Factor		
	70%	*80%*	*90%*
Site Preparation Costs			
Site Design and Layout[c]	—	—	—
Survey and Site Investigations[c]	—	—	—
Legal Searches[c]	—	—	—
Access Rights and Roads[c]	—	—	—
Preparations for Support Facilities[c]	—	—	—
Utility Connections[c]	—	—	—
Auxiliary Buildings[c]	—	—	—
Technology-Specific Requirements	<u>3.67</u>	<u>3.67</u>	<u>3.67</u>
Total Site Preparation Costs	**3.67**	**3.67**	**3.67**
Permitting and Regulatory Costs			
Permits[c]	—	—	—
System Monitoring Requirements[c]	—	—	—
Development of Monitoring and Analytical Protocols[c]	<u>—</u>	<u>—</u>	<u>—</u>
Total Permitting and Regulatory Costs	**—**	**—**	**—**
Equipment Costs			
Major Equipment			
- Detoxifier (\$1,981,000)[d]			
Support Equipment[e]	*0*	*0*	*0*
Equipment Rental	<u>14.24</u>	<u>12.23</u>	<u>11.19</u>
Total Equipment Costs	**14.24**	**12.23**	**11.19**
Startup and Fixed Costs			
Mobilization			
- Transportation	*2.53*	*2.53*	*2.53*
- Assembly	*3.21*	*3.21*	*3.21*
Shakedown	*1.71*	*1.71*	*1.71*
Testing	*1.14*	*1.14*	*1.14*
Working capital	*2.11*	*2.11*	*2.11*
Depreciation (10-year schedule; 65% utilization factor; prorated for assembly, treatment, and disassembly time)	*34.97*	*30.76*	*27.48*
Insurance and Taxes (10% of Equipment Capital Costs; prorated for assembly, treatment, and disassembly time)	*23.55*	*20.71*	*18.50*
Initiation of Monitoring Programs[c]	—	—	—
Contingency (10% of Equipment Capital Costs; prorated for site preparation, assembly, treatment, and disassembly time)	<u>24.40</u>	<u>21.57</u>	<u>19.36</u>
Total Startup and Fixed Costs	**93.62**	**83.74**	**76.05**
Labor Costs			
Supervisory and Administrative Staff	*14.00*	*12.25*	*10.89*
Professional and Technical Staff	*70.03*	*61.28*	*54.47*
Maintenance Staff	*58.11*	*50.85*	*45.20*
Clerical Support[e]	<u>*0*</u>	<u>*0*</u>	<u>*0*</u>
Total Labor Costs	**151.37**	**132.45**	**117.73**

(Continued)

Table 2. Continued

	On-line Factor		
	70%	80%	90%
Supplies Costs			
Raw Materials			
- Chemicals, Health & Safety Gear,			
and Office/General Supplies	10.70	9.41	8.41
Total Supplies Cost	**10.70**	**9.41**	**8.41**
Consumables Costs			
Utilities			
- Fuel	26.17	23.91	20.38
- Water	0.47	0.41	0.36
- Electricity [e,f]	0	0	0
Byproducts and Post-treatment[e]	0	0	0
Total Consumables Cost	**26.64**	**23.33**	**20.75**
Effluent Treatment and Disposal Costs			
On-Site Facility Costs[c]	—	—	
Off-Site Facility Costs			
- Wastewater Disposal[e]	0	0	
- Monitoring Activities[e]	0	0	0
Total Effluent Treatment and Disposal Costs	**0**	**0**	**0**
Residuals and Waste Shipping, Handling, and Transport Costs			
Preparation[c]	—	—	—
Waste Disposal[c]	—	—	—
Total Residuals and Waste Shipping, Handling, and Transport Costs	**—**	**—**	**—**
Analytical Costs			
Operations[e]	0	0	0
Environmental Monitoring[c]	—	—	—
Total Analytical Costs	**0**	**0**	**0**
Facility Modification, Repair, and Replacement Costs			
Design Adjustments[e]	0	0	0
Facility Modifications[e]	0	0	0
Scheduled Maintenance (materials)			
(10% of Equipment Capital Costs,			
60% materials factor, prorated for			
treatment time)	13.62	11.91	10.59
Equipment Replacement[e]	0	0	0
Total Facility Modification, Repair, and Replacement Costs	**13.62**	**11.91**	**10.59**

(Continued)

Table 2. Continued

	On-line Factor		
	70%	80%	90%
Site Demobilization Costs			
Shutdown			
- Disassembly	*3.21*	*3.21*	*3.21*
Site Cleanup and Restoration[c]	—	—	—
Permanent Storage[e]	*0*	*0*	*0*
Total Site Demobilization Costs	**3.21**	**3.21**	**3.21**
Total Cost	**317.06**	**280.23**	**251.58**

[a] *This cost analysis does not include profits of the contractors involved.*

[b] *The American Association of Cost Engineers defines three types of estimates: order of magnitude, budgetary, and definitive. This estimate would most closely fit an order of magnitude estimate with an accuracy of +50% to -30%.*

[c] *These costs are assumed to be the obligation of the responsible party (or site owner) and are not included in the cost estimate.*

[d] *This cost is not used directly but is used for estimating other costs (i.e., depreciation, working capital, insurance and taxes, scheduled maintenance, and contingency).*

[e] *There are no charges associated with these potential cost factors for this technology.*

[f] *For this estimate, it is assumed that electricity is supplied by on-board diesel generators, therefore some of the fuel is used to generate electricity. If electricity is provided by the local utility company, fuel costs decrease and electricity costs increase.*

These costs are considered to be order-of-magnitude estimates as defined by the American Association of Cost Engineers with an expected accuracy within +50% and -30%; however, because this is a new technology, the project contingency is high. These cost values may be different than those normally claimed by TTUSA (see Appendix A, "Vendor's Claims").

Figure 2 presents a breakdown of the costs for each of the twelve cost categories. The results show that, for a treatment rate of 3 yd³/hour, the technology is labor intensive with approximately 47% of the total cost attributed to labor. For higher treatment rates, the technology becomes less labor intensive. The number of employees required could be reduced by working 8-hour days instead of 16-hour days; however, this would increase the number of days required on-site, and in turn increase the overall cost.

For a treatment rate of 3 yd³/hour, only 4% of the costs associated with operating the TTUSA *in situ* steam/hot-air stripper are independent costs. Independent costs are costs that do not depend on site size, transportation distance, or on-line efficiency for any particular treatment rate. This percentage increases with increases in the treatment rate. Site preparation costs are governed by the size of the site; transportation costs vary slightly with the distance traveled to the site. The remaining costs of operation can be reduced by increasing the on-line operating factor and thus decreasing the time required on-site.
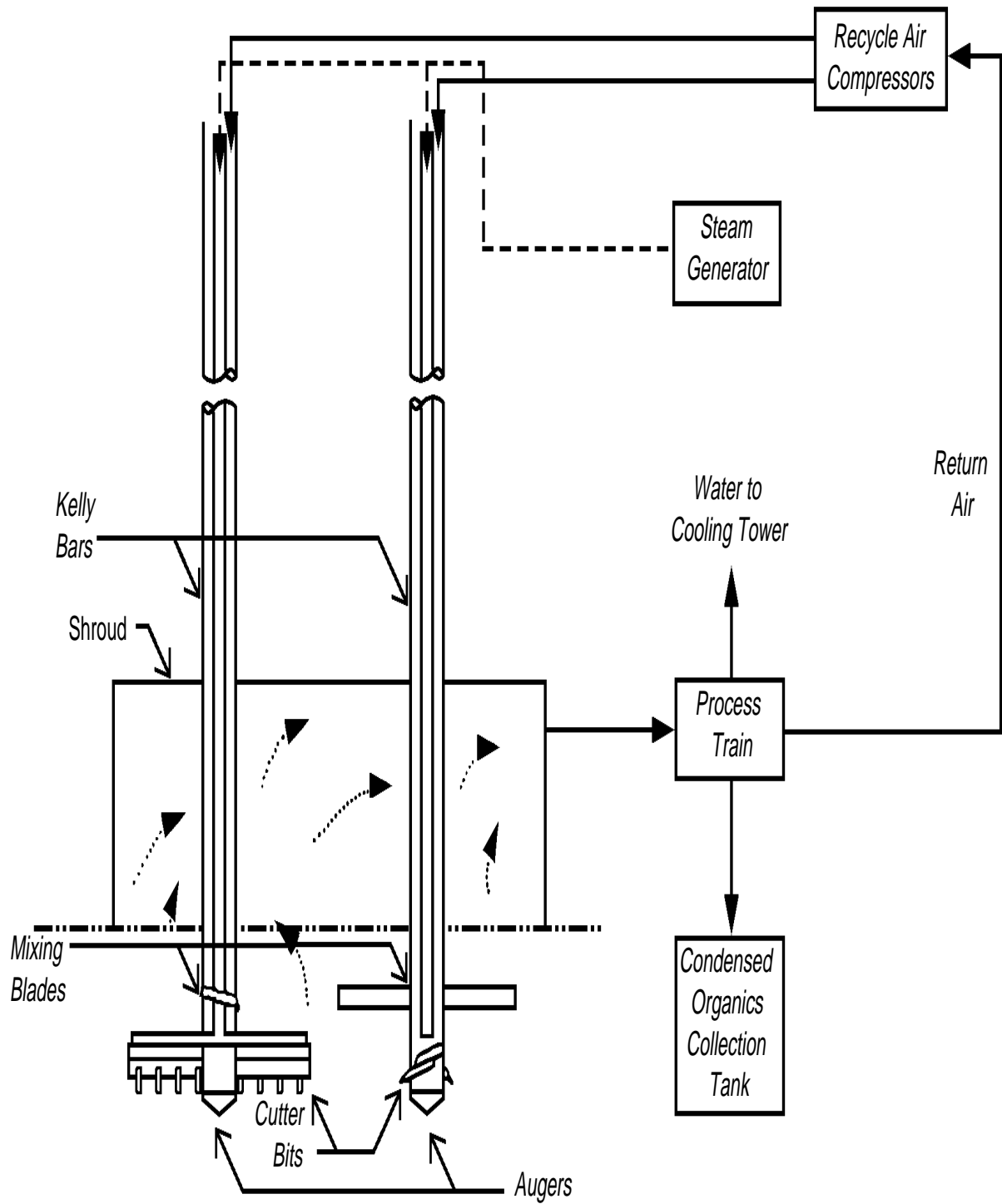
Site preparation costs are minimized when treating a site with few surface and subsurface obstacles. This reduces both the time requirements for initial site preparation and the time

requirements for interruption of treatment when subsurface obstacles are encountered during treatment.

The cost of power can be reduced by approximately 50% if power is supplied directly from the grid system (via the local electric company) rather than from an on-board generator. Presently, the *in situ* steam/hot-air stripper does not operate in this fashion, but may be modified to utilize a transformer for this function. The savings realized by this modification is not substantial, since current power costs represent only about 1% of the total cost per cubic yard.

The results presented above and in Table 2 represent conditions similar to those observed during the Demonstration Test. The demonstration site consisted of clayey soils heavily contaminated with both volatile and semivolatile organic compounds; approximately 3 yd³ were treated per hour with an on-line factor of 70%. Other sites may have more sandy soils, lower levels of contamination, or solely volatile contamination. All of these conditions would significantly increase the number of blocks which could be treated per day. Therefore, results have also been calculated for treatment rates of 6, 10 and 20 yd³/hour. A summary of these results, along with the results for a treatment rate of 3 yd³/hour, is presented in Table 3.

Independent costs range from approximately 4% to 18% of the total costs while labor costs range from approximately 48% to 33% of the total costs for treatment rates of 3, 6, 10 and 20 yd³/hour, respectively. For operation at 3 yd³/hour, independent costs are low and the cost of the technology is labor intensive. Using 3 yd³/hour at 70% on-line as a reference, treatment rates effect the total costs as follows: doubling

Kelly
Bars

Shroud

Mixing
Blades

Cutter
Bits

Augers

Recycle Air
Compressors

Steam
Generator

Water to
Cooling Tower

Return
Air

Process
Train

Condensed
Organics
Collection
Tank

the number of cubic yards treated per hour (to 6 yd³/hour) decreases the total costs by approximately 47%; increasing the number of cubic yards treated per hour by a factor 6.67 (to 20 yd³/hour) decreases the total cost per cubic yard by approximately 79%.

Basis of Economic Analysis

The cost analysis was prepared by breaking down the overall cost into 12 categories. The categories, some of which do not have costs associated with them for this particular technology, are:

- Site preparation costs.
- Permitting and regulatory costs.
- Equipment costs.
- Startup and fixed costs.
- Labor costs.
- Supplies costs.
- Consumables costs.
- Effluent treatment and disposal costs.
- Residuals and waste shipping, handling, and transport costs.
- Analytical costs.
- Facility modification, repair, and replacement costs.
- Site demobilization costs.

The 12 cost factors examined as they apply to the TTUSA *in situ* steam/hot-air stripping process, along with the assumptions employed, are described in detail below.

Site Preparation Costs

It is assumed that preliminary site preparation will be performed by the responsible party (or site owner). The amount of preliminary site preparation will depend on the site. Site preparation responsibilities include site design and layout, surveys and site logistics, legal searches, access rights and roads, preparations for support facilities, decontamination facilities, utility connections, and auxiliary buildings. Since these costs are site-specific, they are not included as part of the site preparation costs in this cost estimate.

Additional site preparation requirements peculiar to *in situ* steam/hot-air stripping are assumed to be performed by the prime contractor (TTUSA). This site preparation, including full removal of surface and subsurface objects (i.e., large rocks, underground piping, etc.), grading, and leveling of the ground to a maximum 1% grade, is required prior to the commencement of treatment. Due to the *in situ* nature of this treatment, and due to the potential treatment depths, it is expected that a few subsurface objects will be discovered during the course of treatment even though the majority of them would have been removed during the site preparation. When they are discovered, treatment will be interrupted and these objects will be removed.

Cost estimates for site preparation are based on operated heavy equipment rental costs; labor charges are included but administrative costs have been omitted. It is assumed that heavy equipment will be rented for approximately one (8-hour) day for each 900 cubic yards undergoing surface and initial subsurface preparation. The minimum equipment required includes: a bladed grader, two large tracked backhoes, and a water truck. Bladed graders are available at an operated

rate of $89/hour; tracked backhoes are available at $132/hour. The rate for an operated water truck is $56/hour. Larger equipment is also available if necessary. In addition to the grader and tracked backhoes, use of a smaller backhoe will be necessary to accommodate any removal of subsurface obstacles encountered during treatment. The small backhoe will need to be on-site for the duration of the treatment. This cost has been incorporated as part of "Equipment Costs".

Permitting and Regulatory Costs

Permitting and regulatory costs are generally the obligation of the responsible party (or site owner), not that of the vendor. These costs may include actual permit costs, system monitoring requirements, and the development of monitoring and analytical protocols. Permitting and regulatory costs can vary greatly because they are very site- and waste-specific. No permitting costs are included in this analysis, however depending on the treatment site, this may be a significant factor since permitting activities can be very expensive and time-consuming.

Equipment Costs

Equipment costs include major pieces of equipment (the *in situ* steam/hot-air stripper), purchased support equipment (none), and rental equipment. Support equipment refers to pieces of purchased equipment necessary for operation. Items such as a small backhoe, a 60-kW generator, a steam-cleaning unit, and a truck may be purchased by TTUSA as support equipment, however, to provide a conservative cost estimate, all necessary support equipment is assumed to be rented.

The *in situ* steam/hot-air stripper used during the Demonstration Tests is the ATW Detoxifier, Model 1M, manufactured by Calweld, Inc. This model is a prototype, assembled from used parts. The cost of the prototype *in situ* steam/hot-air stripper is $1,981,000. Costs for future models are anticipated to be slightly higher if provided by the same manufacturer.

Various types of rental equipment will be necessary for the duration of the project. Rental equipment includes: a small backhoe, a generator, a steam-cleaning unit, a truck, and facilities equipment. Weekly and monthly rates are available in some cases and may represent significant savings, depending on the site and the type of equipment rented. Liquid storage tanks are also required, but this cost is directly related to waste disposal and is assumed to be the obligation of the responsible party or site owner. Costs for storage tank rental are reported under "Effluent Treatment and Disposal Costs" and "Residuals and Waste Shipping, Handling and Transport Costs".

The backhoe will need to be on-site for the duration of the treatment; TTUSA personnel will operate and maintain the backhoe. A small backhoe (without tracks) is available at a rate of $2,580/month (bare rental). Backhoes are rented based on normal use (8 hours/day). Rental fees are two times the base rate for operation 16 hours/day.

The majority of the remaining rental charges have been calculated on a monthly basis and the equipment is assumed to be on-site for the duration of the project (including site preparation, assembly, and disassembly time). A 60-kW generator will be required to supply power to the office facilities.

Table 3. Summary of Estimated Costs in $/Cubic Yard for Various Treatment Rates and On-line Operating Factors[a,b]

	3 Cubic Yards/Hour			6 Cubic Yards/Hour			10 Cubic Yards/Hour			20 Cubic Yards/Hour		
	70%	80%	90%	70%	80%	90%	70%	80%	90%	70%	80%	90%
Site Preparation Costs	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
Permitting and Regulatory Costs	0	0	0	0	0	0	0	0	0	0	0	0
Equipment Costs	14.24	12.53	11.19	7.37	6.51	5.85	4.62	4.11	3.71	2.56	2.30	2.10
Startup and Fixed Costs	93.62	83.74	76.05	54.05	49.14	45.29	38.26	35.30	32.98	26.39	24.92	23.77
Labor Costs	151.37	132.45	117.73	75.68	66.22	58.87	45.41	39.73	35.22	22.71	19.87	17.66
Supplies Costs	10.70	9.41	8.41	5.54	4.90	4.40	3.48	3.09	2.79	1.93	1.74	1.59
Consumables Costs	26.64	23.33	20.75	13.38	11.72	10.43	7.99	7.08	6.30	4.09	3.60	3.21
Effluent Treatment and Disposal Costs	0	0	0	0	0	0	0	0	0	0	0	0
Residual and Waste Shipping, Handling, and Transport Costs	0	0	0	0	0	0	0	0	0	0	0	0
Analytical Costs	0	0	0	0	0	0	0	0	0	0	0	0
Facility Modification, Repair and Replacement Costs	13.62	11.91	10.59	6.81	5.96	5.30	4.08	3.57	3.18	2.04	1.79	1.59
Site Demobilization Costs	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21	3.21
Total Cost	317.06	280.23	251.58	169.74	151.32	137.00	110.73	99.76	91.16	66.61	61.09	56.79

[a] This cost analysis does not include profits of the contractors involved.
[b] The American Association of Cost Engineers defines three types of estimates: order of magnitude, budgetary, and definitive. This estimate would most closely fit an order of magnitude estimate with an accuracy of +50% to -30%.

21

Generators are available at a rate of $1,000/month. Generators are rented based on normal use (8 hours/day). Rental fees are 1.5 times the base rate for operation 16 hours/day. A steam-cleaning unit will need to be on-site for the duration of the project to facilitate decontamination of the equipment. Steam-cleaning units are available at a rate of $300/month. A truck will be required to perform miscellaneous hauling activities. Trucks are available at a daily rate of $55.

Facilities equipment is presumed to include two office trailers ($300/month each), one lot of furniture ($200/month), 2 telephones ($100/month each), a computer ($300/month), and a portable toilet ($70/month).

Startup and Fixed Costs

Mobilization includes both transportation and assembly. The *in situ* steam/hot-air stripper is a mobile unit designed to move from site to site, thus transportation costs are only charged to the client for one direction of travel. For the purpose of this estimate, transportation charges are included with mobilization rather than demobilization.

Transportation costs are broken down into trucking costs and costs associated with transporting the crew to the site. Trucking charges include drivers and are based on a 40,000-pound legal load. Five tractor/trailers are required. A 1,000-mile basis is assumed at a rate of $1.50/mile/40,000-pound load. One of the tractor/trailers requires a permit for oversize/overweight load. A $4,000 permit fee is estimated for this oversize/overweight load; permitting costs are assessed by individual states and vary from state to state. The permitting costs vary with the number of state lines crossed. Transportation costs for the 12-man crew are based on a $300 one-way airfare per person. Some TTUSA personnel may choose to drive their own vehicle to the site, but transporation costs, accounting for mileage, would essentially be the same. TTUSA may also elect to hire local personnel and transportation costs would be reduced accordingly.

Assembly consists of unloading the equipment from the trucks and trailers used for transportation, as well as actual assembly. Unloading requires the use of an operated 30-ton crane, available at $200/day, for one 16-hour day. Assembly requires a full (12-man) crew working five 16-hour days (one week). Labor costs include salary and living expenses. See "Labor Costs" for information on how labor rates are obtained.

Each project requires one week for baseline calibration prior to the commencement of treatment. Three 16-hour days are allotted for shakedown purposes. This includes checking out each of the systems individually prior to starting up the entire *in situ* steam/hot-air stripper. The cost of shakedown is limited to labor charges (including living expenses). Some testing of the equipment must be performed. This testing includes actual drilling time which allows soil characteristics and temperatures achieved to be evaluated prior to treatment. Testing is assumed to require approximately two 16-hour days. Testing costs are based on labor charges (including living expenses).

Working capital consists of the amount of money currently invested in supplies, fuel, and spare parts kept on hand.

The working capital costs of supplies and fuel is based on maintaining a one-month inventory of these items. Working capital costs of spare parts is estimated as 0.5% of the total equipment capital costs (1.981 M). The total working capital cost for this project is $18,862.

The depreciation cost is based upon a 10-year life for the equipment. The depreciation, based upon the writeoff of $1,981,000 worth of new equipment and $198,100 (10%) scrap value at the end of 10 years, is $178,290. A 65% utilization factor has been incorporated to account for depreciation that occurs while the equipment is not on any worksite. Maintenance, marketing, and regulatory delays are activities which take place between projects and make up approximately 35% of the total availability of the equipment. This depreciation cost has been prorated to the actual time spent on-site (including assembly, treatment, and disassembly).

Insurance and taxes together are assumed for the purposes of this estimate to be 10% of the equipment capital costs. These costs have been prorated to the actual time spent on-site (including assembly, treatment, and disassembly).

The cost of initiation of monitoring programs has not been included in the scope of this estimate. The nature of *in situ* steam/hot-air stripping does not require any monitoring beyond standard operating procedures. Health and safety monitoring costs have been incorporated into labor and supply costs. Depending on the site, however, local authorities may impose specific guidelines for monitoring programs. The stringency and frequency of monitoring required may have significant impact on the project costs.

A contingency cost of approximately 10% of the equipment capital costs is allowed for any unforeseen or unpredictable cost conditions. The annual cost of contingency is prorated to the actual time spent on-site (including site preparation, assembly, treatment, and disassembly).

Labor Costs

Labor costs may be broken down into two major categories: living expenses and salaries. Living expenses for all personnel (except clerical support who, if required, are assumed to be local hires) consist of per diem and rental cars, both estimated at 7 days/week for the duration of the treatment. Per diem is assumed to be $100/day/person, but may vary by location. Three rental cars are assumed to be obtained at a rate of $30/day. Should TTUSA elect to hire local personnel other than clerical, living expenses would be reduced by a factor proportional to the number of local hires.

Supervisory and administrative staff is limited to a single site supervisor at a rate of $40/hour. Professional and technical staff includes two health and safety engineers ($50/hour) and four operators ($30/hour). Maintenance personnel consists of five mechanics at a rate of $30/hour. Clerical support is not anticipated on a typical project. If necessary, secretaries are available locally at an hourly rate of $15. This staffing is the minimum required for double shift operation. Rates include overhead and administrative costs; it is assumed that personnel will work an average of 40 hours/week.

Supplies Costs

Based on data from previous operations, over a period which reflects operating conditions similar to those experienced during the Demonstration Test, the costs for chemicals, health and safety gear, and office/general supplies are estimated at $7,500 per month (16-hour days) for this technology. Chemicals are limited to those necessary for treatment of the boiler and cooling tower water. Health and safety gear is assumed to include: hard hats, safety glasses, respirators and cartridges, protective clothing, gloves, safety boots, and a photoionization detector monitoring instrument.

Consumables Costs

Diesel fuel is assumed to be supplied by a local distributor at $1.03/gallon. Diesel fuel prices, however, fluctuate with supply and demand and current market prices may impact this cost.

Nonpotable water is available from the City of Los Angeles. Since rates in California are governed by the time of year, it has been assumed that the entire treatment occurs in the summer months in California to provide a conservative estimate. Billing is broken down into four categories, with the total charges being the sum of the charges for these categories. Rates are as follows:

1.5-inch line	=	$8.40/month
Summer rate	=	$0.805/100 ft^3
Adjusted rate	=	$0.381/100 ft^3
Sewer charge (commercial rate)	=	$0.868/100 ft^3

All electric power utilized by this technology is supplied via a 250-kW generator located on the process train and thus the cost of electricity is incorporated into the fuel charges. Since the *in situ* steam/hot-air stripper may be modified to utilize power supplied directly from the grid system (via the local electric company), local electricity rates are also used to estimate the cost of the power utilized by the system. This cost information can be used to draw a comparison between the expense of operation using a generator to provide electricity versus operation using electricity from the grid system.

Electricity is available from the City of Los Angeles. For small business customers whose power usage is up to 7,200 kWh/month, an A1 rate applies. "Time-of-use" billing is optional. This enables a customer to obtain lower rates for off-peak usage. Again, billing is broken down into two categories, and the total charge is the sum of the charges assessed in the two categories.

Flat rate	=	$0.08999/kWh
Service charge	=	$0.30/month
"Time-of-use" rate (optional)		
Peak hours	=	$0.13197/kWh
Off-peak hours	=	$0.06426/kWh
Service charge	=	$0.30/month

Assuming operating hours are from 6:00 a.m. to 10:00 p.m., this results in 8 hours of peak hour operation and 8 hours of off-peak hour operation. The "time-of-use" rate is not beneficial in this case since the average "time-of-use" rate ($0.09812/kWh) is greater than the flat rate ($0.08999/kWh).

No byproducts are generated by this process. Furthermore, it is assumed that the process does not produce any streams that require post-treatment. Normal operation of the system is inclusive of treatment and processing of all process streams.

Effluent Treatment and Disposal Costs

Only one effluent stream is anticipated for the *in situ* steam/hot-air stripping process. This stream is the wastewater generated from boiler and cooling tower blowdown that is pumped to the water storage tank daily. On-site facility costs are restricted to on-site storage of the wastewater and assumed to be the obligation of the site owner or responsible party. Liquid storage tanks are rented at a daily rate. These costs will accrue over weekends as well as weekdays. One liquid storage tank will be necessary for wastewater storage prior to disposal. Liquid storage tanks are available from a Long Beach distributor, Baker® Tanks, Inc. It is assumed that the wastewater will be stored in an open tank. Open liquid storage tanks are available in a 9,700 gallon size for $10.50/day. Delivery and pickup charges are each $220/tank.

Off-site facility costs are assumed to consist of wastewater disposal fees. Wastewater is assumed to meet local water quality standards. It will be pumped from the water storage tank and will either be used for dust control purposes or will simply be evaporated from the decontamination pad on-site. Charges for disposing of the wastewater in this manner are essentially zero. No monitoring activities are associated with this action. If off-site disposal is required by local regulatory authorities, the water will be pumped from the water storage tank and disposed of by an appropriate firm at a cost of approximately $1/gallon.

Should the wastewater contamination exceed regulated levels, the wastewater is then classified as a waste (rather than an effluent) and will either be recycled or disposed of as a hazardous waste. In the first case, wastewater will be recycled through the process train to diminish organic contaminant levels in this stream. Although the quantity of wastewater will not change significantly, recycling demands will contribute an additional expense to "Effluent Treatment and Disposal Costs" and will slightly increase condensed organic quantities, that contributes an additional expense to "Residuals and Waste Shipping, Handling, and Transport Costs" (see below). In the latter case, "Effluent Treatment and Disposal Costs" are reduced to storage fees, but "Residuals and Waste Shipping, Handling, and Transport Costs" are substantially increased due to the quantities of wastewater generated and the high cost of hazardous waste disposal.

Residuals and Waste Shipping, Handling and Transport Costs

Waste disposal costs include storage, transportation and treatment costs and are assumed to be the obligation of the responsible party (or site owner). It is assumed that residual or solid wastes generated from this process consist only of contaminated health and safety gear, used filters, and spent

activated carbon. Landfill is the anticipated disposal method for this material at an estimated cost of $100/drum.

It is assumed that the only liquid waste generated by this process is the condensed organics stream produced by treatment of the organic contaminants removed from the soil. The waste stream is processed until the majority of the water is removed and the liquid organics are stored until they can be transferred into a vessel suitable for hazardous waste transport. Removal of excess water results in a highly concentrated organic waste stream and minimizes costs for hazardous wastewater disposal. It is assumed that the organics will be stored in a single covered liquid storage tank, sealed to ensure no loss of organics. Covered liquid storage tanks (9,700 gallons) are available for $11/day. Covered liquid storage tanks are rented at a daily rate, and these costs will accrue over weekends as well as weekdays. Delivery and pickup charges are each $220/tank.

The condensed organics will require treatment prior to their ultimate disposal. The organics will be transported to a disposal site for incineration. Costs for transportation and incineration are assumed to be approximately $0.50/gallon. A second option for disposal of the condensed organics stream is recycling the material as a fuel additive in a cement kiln. The costs for this type of treatment are slightly lower (approximately $0.25/gallon, including transportation).

Analytical Costs

No analytical costs during operations are included in this cost estimate. Standard operating procedures for TTUSA do not require planned sampling and analytical activities. Periodic spot checks may be executed at TTUSA's discretion to verify that equipment is performing properly and that cleanup criteria are being met, but costs incurred from these actions are not assessed to the client. The client may elect, or may be required by local authorities, to initiate a sampling and analytical program at their own expense.

The analytical costs associated with environmental monitoring have not been included in this estimate due to the fact that monitoring programs are not typically initiated by TTUSA. Local authorities may, however, impose specific sampling and monitoring criteria whose analytical requirements could contribute significantly to the cost of the project.

Facility Modification, Repair and Replacement Costs

Maintenance labor and materials costs vary with the nature of the waste and the performance of the equipment. For estimating purposes, total maintenance costs (labor and material) are assumed to be 10% of equipment capital costs on an annual basis. The ratio of labor/materials costs is typically 40/60. Maintenance labor has previously been accounted for under "Labor Costs"; maintenance materials costs are estimated at 60% of the total maintenance and prorated to the time required for treatment. Costs for design adjustments, facility modifications, and equipment replacements are included here.

Site Demobilization Costs

Disassembly consists of taking the *in situ* steam/hot-air stripper apart and loading it onto trailers for transportation. It requires the use of an operated 30-ton crane, available at $200/hour, for one 16-hour day. Additionally, disassembly requires a full (12-man) crew working five 16-hour days (one week). Labor costs include salary and living expenses. Since this cost is fixed, it is included here. See "Labor Costs" for information on labor rates.

Site cleanup and restoration is limited to the removal of all equipment and facilities from the site. These costs have been previously incorporated into the disassembly and equipment rental charges. Grading or recompaction requirements of the soil will vary depending on the future use of the site and are assumed to be the obligation of the responsible party.

References

1. "Low-Cost Cleanup of Toxic Petrochemicals," CBE News, December 12, 1988.

2. *Federal Register*, Volume 55, No. 61, March 29, 1990.

3. *Federal Register*, Volume 50, No. 230, November 29, 1985.

Appendix A
Vendor's Claims

This appendix summarizes the claims made by the developer, Toxic Treatments (USA), Inc. (TTUSA), regarding *in situ* steam/hot-air stripping, the technology under consideration. This appendix was generated and written solely by TTUSA and the statements presented herein represent the vendor's point of view. Publication here does not represent EPA's approval or endorsement of the statements made in this section; EPA's point of view is discussed in the body of this report.

Introduction

The Detoxifier is a patented (US #4,776,409), mobile treatment unit used in the *in situ* remediation of contaminated soils and waste deposits. The soil is treated in place and is not excavated or removed to the surface.

The commercial prototype of the system has undergone extensive testing under contract with the responsible party at a site in San Pedro, California. The site, which is under the control of the California Department of Health Services, is contaminated with chlorinated hydrocarbons at concentrations up to 10,000 parts per million (ppm), as well as other VOCs and semivolatile compounds (SVCs) which range from a few parts per million up to 20,000 to 50,000 ppm. The average of total organic compounds is in the 500 to 1,000 ppm range.

Operations prior to and since the SITE demonstration (which was conducted on the San Pedro site) in the vadose zone and in saturated soil have resulted in the removal of an average of approximately 97% of volatile contaminants (based on analysis using SW-846 Method 8240). Semivolatile hydrocarbons (SW-846 Method 8270) have been reduced by an average of 86%; this result was unexpected due to the high vapor pressure of the SVCs in relation to the temperature generated by the system. This removal efficiency is attributed to potential chemical reactions catalyzed by the clay soil, steam distillation, and the formation of low boiling azeotropes of hydrocarbons. Noise and air emissions during operation are below the limits set by regional environmental regulations in Southern California, and no undesirable environmental effects have been identified.

Potential Application

The Detoxifier is capable of a wide range of site remediation methods, including:

- Steam/hot-air stripping of volatile contaminants.

- Solidification/stabilization and construction of containment structures by addition of chemicals or physical agents (e.g., pozzolanic materials).

- Neutralization or pH adjustment by addition of acids or bases.

- Destruction or chemical modification of contaminants via use of oxidizing or reducing chemicals.

- Addition of micro-organisms, nutrients and oxygen to promote *in situ* biodegradation.

These methods may be applied to the treatment of volatile and semivolatile hydrocarbons, heavy metals, and other organic and inorganic compounds. As of the date of this SITE report, the Detoxifier has only been used in an *in situ* steam/hot-air stripping application to remove volatile and semivolatile hydrocarbons.

System Advantages

The Detoxifier is an environmentally sound system for the remediation of contaminated soil. It affords the following advantages over many other treatment systems:

- *In situ* remediation, eliminating the requirement of excavation, transportation and disposal of contaminated material.

- Permanent treatment, limiting health effects and responsible party liability.

- Closed-loop system, preserving air quality and reducing worker exposure.

- Versatility, providing treatment of a wide range of organic and inorganic contaminants.

- Treatment efficiency, utilizing real-time measurement of contamination and achievement of remediation levels (in hydrocarbon stripping applications).

- Treatment speed, due to the mixing action of the blades and energy contained in the steam and air jets, the Detoxifier cleans the soil quickly.

- Transportable, permitting movement from site-to-site.

The Detoxifier is also believed to be a cost-effective method of remediating contaminated soil. Because of limited

experience in commercial operations, however, actual cost data are limited. (See "Cost Information" below.)

The Process

The Detoxifier consists of a process tower, a control unit, and a chemical process train. These components are configured to meet site-specific requirements and vary depending on site conditions and characterization.

The process tower is essentially a drilling and remediation-agent dispensing system, capable of penetrating the soil medium to depths of 30 feet with the current equipment; equipment with capability up to 75 feet can be built. Remediation agents are added to and mixed with the soil at various depths by the drill head assembly. The drill head assembly is composed of two drill blades, each five feet in diameter with injection dispensers. A box-shaped shroud, under vacuum, covers the drill head assembly to isolate the treatment area and prevent any environmental release. The process tower assembly is mounted on a modified Caterpillar chassis.

The control system consists of process monitoring and control instrumentation. In-line analytical instruments continuously monitor and record treatment conditions. Flame ionization detectors (FIDs) monitor the concentration of total hydrocarbons at select process locations, including the off-gas from the shroud and the purified return air. A gas chromatograph (GC) provides periodic data on the identification and concentration of specific compounds in the off-gas stream. The output of the FIDs, GC, temperature sensors, depth gauge, and other instrumentation is stored in a computerized data logging system, displayed on a terminal and recorded on a strip chart recorder. The monitoring data are used to control and optimize the treatment process and determine the achievement of remediation objectives.

The chemical process train consists of either treatment systems to decontaminate off-gases and/or feed systems for the injection of remediation agents. Remediation agents may be in dry, liquid, vapor or slurry form, depending on the nature of the contaminants.

Treatment systems to decontaminate off-gases: In applications involving *in situ* steam/hot-air stripping of volatile and semivolatile hydrocarbons, the off-gas containing the contaminants is captured in the shroud and sent in a closed loop (to prevent any environmental release) to a trailer-mounted chemical process train for removal of water and chemical contaminants; the clean air is then recycled to the soil treatment zone. The liquid contaminant residue is either recycled or disposed of off-site. Each chemical process train for the treatment of off-gases contains modules to remove select contaminant mixtures by scrubbing, condensation, and adsorption. Typically, an off-gas treatment train includes induced draft fans for gas conveyance and recycling; scrubbers for the removal of particulates; cooling and refrigeration systems for condensing the bulk of the volatiles; a distillation unit to separate hydrocarbons from water; activated carbon adsorption units and gas monitoring systems.

Feed systems for the injection of remediation agents: In applications involving *in situ* treatment with only the addition and mixing of remediation agents to the soil without the need to process off-gas, the chemical process train consists of chemical containers, measurement instrumentation and a pumping system to feed remediation agents to the drill head assembly. Steam and hot air are injected into the soil to remove VOCs. The steam and hot air are injected into and distributed within the ground by means of a pair of hollow kelly bars and rotating mixing blades five feet in diameter. The VOCs are evaporated from the soil matrix into the remediation air stream. These off-gases move up beside the kelly bars to the surface and are collected in a metal shroud, which is under a slight vacuum. A blower mounted on a separate process chassis extracts the air and vapors, along with a small amount of dust, from the shroud and directs them to a process train where the contaminants are removed and collected for recycling or disposal.

The remediation of a large area is carried out by a block-by-block treatment. The area to be remediated is divided into rows of blocks, with the process tower, control unit and process treatment train being moved from one block to the next after the remediation of a block is completed. To assure complete coverage of the area to be remediated, the drill assembly is positioned with a 20% overlap of the previously treated block. The net surface area of a treatment block is approximately 29 ft^2. The volume of each block is determined by the depth of remediation with each foot of depth equaling approximately one cubic yard of material.

System Limitations

Use of the Detoxifier system may be limited by both physical and chemical characteristics of a contaminated site.

Physical Limitations

Because the system involves penetration of the soil, the surface must be free of obstructions such as hard pavement, buildings or other structures, and the subsurface must be free of major obstructions such as large boulders, concrete footings or water/sewage mains, and steel pipe several inches in diameter. The system has operated in soil containing boulders and cast iron pipes up to 12 inches in diameter, 2-inch by 12-inch planks, and rusty oil barrels. New equipment under construction will have greater power and torque, thus permitting operations with more significant subsurface obstructions.

Use of the current prototype system in *in situ* steam/hot-air stripping applications is limited to flat surfaces with not more than 1% grade. The new design of the system will permit operations with grades up to 5%.

Chemical Limitations

The system, which operates at about 180°F (75°C), appears to effectively remove organic chemicals with boiling points of less than 300°F (150°C). Compounds with higher boiling points become more difficult to remove by the vaporization process, and those with boiling points in excess of 400°F may not be economic to remove. However, many of the high boiling organic compounds are removed by steam distillation, i.e., formation of organic azeotropes or a steam-organic azeotrope. Experience to date has confirmed this result. At the current site, phenol, naphthalene, and isophorone are often removed to more than 95%, and, even though only minor quantities of polyaromatic hydrocarbons (PAHs) are found in

the soil prior to treatment, significant quantities of all PAHs up to chyrsene have been found in the carbon beds. Post-treatment soil samples generally show removal of PAHs to below the detection limit. This is believed to occur via steam distillation.

The process requires increased treatment times in high clay soils. Experience indicates that soils with 70% clay require twice the treatment time as 30% clay (the remainder silt and fine sand). Thus, high clay soils may be too costly to treat unless a site has sandy regions to reduce average treatment time. The process is much more efficient when treatment depths are greater and also when treating into a saturated zone containing sand and silt. Greater depth not only adds efficiency, but also takes advantage of the sweeping movement of the operation. Working in the saturated zone in sand and silt soil matrix increases efficiency because the air can penetrate deeply into the soil which acts like a floating bed reactor. Treatment rates have been improved 2 to 3 times.

The process has demonstrated significant removal of semivolatile compounds (e.g., glycol ethers, bis(2-ethylhexyl)phthalate, other phthalates and adipates) by a variety of processes, some believed to be catalyzed by clay in the soil. The reasons for these results are being studied in an attempt to quantify them and control them. The effectiveness of the Detoxifier in removing these semivolatiles must be further determined by additional field or laboratory studies.

Cost Information

Detoxifier treatment cost data are expressed in dollars per cubic yard of material treated. The rate varies significantly depending on the following major factors:

- Nature and concentration of contamination.
- Physical properties of the soil being treated.
- Size and depth of the contaminated area.
- Proximity of the site to the company's geographical region.

The following estimates include all direct, indirect, administrative, and overhead costs as well as profit. The cost estimates are based on an *in situ* steam/hot-air stripping operation. As previously stated, the company does not have any operational or developmental experience in a neutralization, solidification, chemical modification, or biodegradation application of the Detoxifier. It is estimated, however, that the cost of such applications will be significantly less than a steam/hot-air operation because of reduced equipment and labor requirements.

Excluded from project costs are expenses associated with soil sampling, chemical analysis, and the transportation and disposal of contaminant residues.

Costs are extremely sensitive to treatment rates, which are determined by site characteristics. It therefore is realistic to quote a range of client costs due to the widely divergent nature of site characteristics. The estimates for an *in situ* steam/hot-air stripping application are presented in Table 4 and are based on experience at the SITE Demonstration site, assuming a two-shift operation at a site within 500 miles of the company's location and containing 12,000 cubic yards of material to be treated.

It should be emphasized that these estimated costs are based on the company's operations to date with the commercial prototype of the Detoxifier. The costs should be reduced with additional operating experience and follow-on generations of equipment.

Table 4. Vendor's Cost Estimates

| | Treatment Rate (yd³/hour) | | |
	5	10	20
Project duration (months)	8.08	4.62	2.88
Estimated cost ($/yd³)	$325	$200	$125

Appendix B
SITE Demonstration Test Results

The contaminated site was divided into 1,643 treatment blocks (7 feet-4 inches by 4 feet). Twelve of the blocks in Area A were treated only to the water table (5 feet below the soil surface) during the Demonstration Test. These blocks were sampled before and after treatment in accordance with the Demonstration Plan [1]. An additional six blocks (also in Area A), which were treated to below the full zone of contamination, were sampled after treatment only.

Volatiles in Soil

Levels of volatile organics in the soil were measured by obtaining composite soil core samples before and after treatment by the *in situ* steam/hot-air stripping technology. The results are summarized in Table 1 in the body of this report. For the entire 12-block test area (grouping all composite sample data points) the total volatile compounds identified by SW-846 Method 8240 in the soil before treatment had an average concentration of 466 ppm with a standard deviation of 457 ppm. The 95% confidence interval range for the true mean of the pre-treatment cores was 315 to 618 ppm. After treatment, the average concentration of total volatile compounds identified by Method 8240 was 71 ppm. The standard deviation for the post-treatment cores was 80 ppm. The 95% confidence interval range for the true mean of the post-treatment cores was 45 to 98 ppm. The high standard deviation in the samples is indicative of the inhomogeniety of the contamination at the site. Based on the average pre- and post-treatment data, the effective removal efficiency for volatile compounds identified by Method 8240 was approximately 85%. Chlorobenzene, trichloroethene, and tetrachloroethene were the predominant compounds detected.

The block-to-block variation of post-treatment concentration of volatiles in composite samples obtained from the 12-block test area was substantial. Using the average of the three post-treatment cores in each block, the concentration varied from 12 to 196 ppm. The concentration of individual cores varied from 5 to 355 ppm. This high amount of variability was unexpected since previous data from TTUSA had indicated that they were able to treat the blocks in Area A consistently to below 100 ppm using a treatment protocol similar to the one used during the SITE demonstration.

Levels of volatile organics in the soil after treatment were also measured in a separate 6-block test area where treatment extended into and below the water table and below the zone of contamination. For the entire 6-block test area (based on all composite data points), the total volatile compounds identified by SW-846 Method 8240 in the soil following treatment with the alternative treatment protocol was 53 ppm with a standard deviation of 73 ppm. The 95% confidence interval range for the true mean of the post-treatment cores in this area was 19 to 87 ppm. In the 6-block test area, ketones (specifically acetone, 2-methyl-4-pentanone, 2-butanone) were found to be the primary compounds remaining following treatment. Only one discrete pre-treatment sample was obtained from this area; additional data was not obtained prior to treatment.

Using the three composite cores obtained from each block to determine the average concentration in a block, average block concentration ranged from 16 to 119 ppm in the 6-block test area. Concentrations in the individual cores ranged from 7.2 to 284 ppm.

Semivolatiles in Soil

The *in situ* stripping technology was not designed to remove semivolatiles from the soil. Nonetheless, semivolatile compounds were reduced by approximately 55% in the 12-block test area based on analysis of soil cores. However, no substantial amounts of semivolatiles or their potential treatment reaction products were found in the condensed organics collection tank. The average pre-treatment semivolatile concentration of compounds identified by Method 8270 was 902 ppm with a standard deviation of 469 ppm. The 95% confidence range for the true mean lies between 742 and 1062 ppm. The average post-treatment semivolatile concentration was 409 ppm. The 95% confidence interval for the true mean of post-treatment cores was 237 to 581 ppm; the standard deviation was 407 ppm. Block-to-block reduction varied from 7% to 95% among the 12 blocks in the treatment area. (See Table 5.)

The major semivolatile organic compound found in the post-treatment soil was bis(2-ethylhexyl)phthalate, with a concentration ranging from 4.6 to 1,200 ppm. Other compounds found in lesser concentrations were phenol, naphthalene, and phenanthrene.

Dye Studies

Fluorescein dye was added to the soil at a depth of 3.5 feet prior to the treatment to serve as a tracer for determining the post-treatment homogeneity of the soil and for evaluating the downward migration of contaminants. The dye concentrations were found to be variable through the treatment blocks

Table 5. Demonstration Test Results for Semivolatiles

Block Number	Pre-Treatment (μg/g)	Post-Treatment (μg/g)	Percent Reduction (%)
A-25-e	595	82	86
A-26-e	1117	172	85
A-27-e	1403	439	69
A-28-e	1040	576	45
A-29-e	1310	726	45
A-30-e	1073	818	24
A-31-e	781	610	22
A-32-e	994	49	95
A-33-e	896	763	15
A-34-e	698	163	77
A-35-e	577	192	67
A-36-e	336	314	7
Avg[a]	902	409	55
Std Dev[a]	469	407	NA[b]

[a] Reported for the entire treatment area, based on analysis of all composite cores.
[b] Not applicable.

after treatment. The highest concentrations of dye were found in the 4 to 5.5 foot range indicating that the treatment had reached the bottom of the block. Occasional smaller peaks were found below the treatment area, although it was not clear whether this was an artifact of the sampling technique; the dye peaks below the five foot depth were always found at the interface of two cores. Figure 3 graphically depicts these results.

Condensed Organics

The condensed organics, collected in the holding tank, formed two distinct phases. The bottom phase was essentially all organics, while the top phase consisted nearly entirely of water. A total of 1240 L of condensed organics were collected during treatment of the 12-block test area. The three major compounds in the condensed organics were the same as those found in the soil. The approximate concentrations of the major organics in the bottom phase were:

- Trichloroethene - 36%
- Tetrachloroethene - 30%
- Chlorobenzene - 22%

The total concentration of semivolatile organic compounds was less than 0.3% in the bottom phase. The top phase contained about 1% volatile organics and less than 100 ppm semivolatile organics.

Treated Water

The treated water coming from the wet carbon filter into the cooling tower contained small residual amounts of VOCs. The average treatment efficiency for the wet carbon filter was found to be 97%. The total amount of volatile compounds detected by Method 8240 in the treated water for the entire twelve-block test area was 620 grams. The average concentration was about 8 ppm. The main compounds detected in the treated water were acetone, tetrachloroethene, and trichloroethene.

Fugitive Emissions

Fugitive emissions were measured using the flux chamber technique from the area around the shroud during treatment and from the block that had just been treated (after removal of the shroud). Three soil treatment blocks were measured. In all three cases, the highest emission rates were measured from Location 3 which sampled the block which had just undergone treatment immediately after removal of the shroud (see Figure 1 in the body of this report).

Table 6 summarizes the results of the fugitive emission sampling. The total measured fugitive emissions of organic compounds from the three heavily contaminated blocks averaged less than 22 grams. Assuming that 6 blocks with similar levels of contamination are treated each 16-hour day during remediation, the total organic emissions from the blocks would be less than 140 grams per day (about 0.3 pounds per day).

TCLP Results

Although *in situ* treatments are not subject to land ban regulations, one sample core from both the pre-treatment and post-treatment soil was subjected to TCLP extraction and analysis to determine the amount of leachable volatile and semivolatile compounds, as well as leachable metals in the soils. Duplicate samples were analyzed for organics and metals; they showed significant variabililty for pre- and post-treatment samples. The results for metals for both pre- and post-treatment analyses are well below the EPA regulatory limits found in the *Federal Register* [2] for all of the components. The post-treatment leachate for all organics was below the regulatory limits.

Physical Tests

Each core from the pre- and post-treatment sampling was measured and sampled to determine percent moisture, bulk density, and specific gravity. Table 7 summarizes these results. Based on statistical analysis, there is essentially no difference in the moisture content and the bulk density of the soil between pre-and post-treatment.
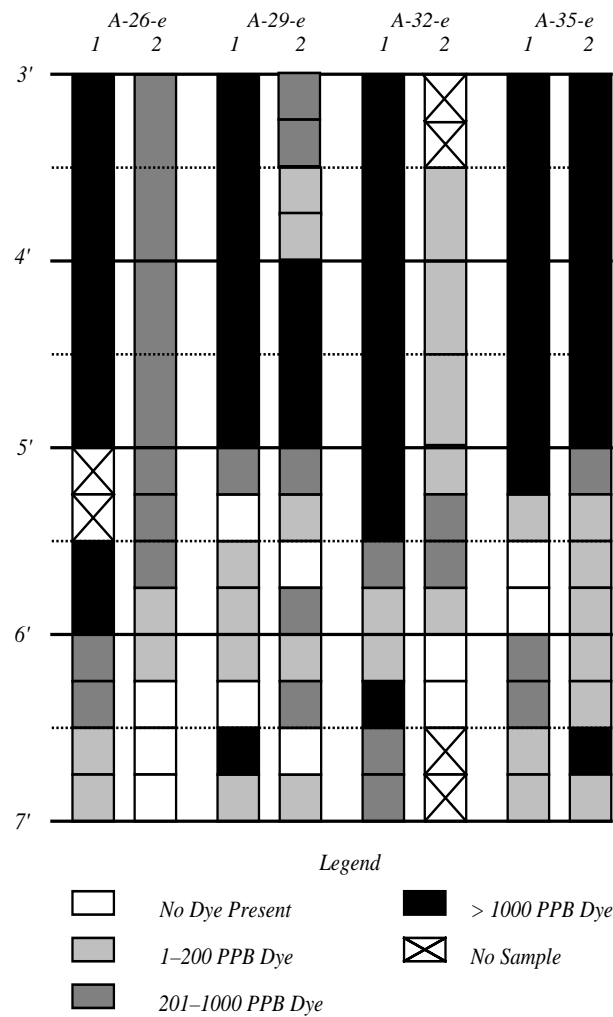
Figure 3.   *Demonstration results for fluorescein dye.*

<table>
<tr><td colspan="6">Table 6.   Fugitive Emissions From Blocks A-28-e, A-29-e, and A-30-e</td></tr>
<tr>
<td>Block Number</td>
<td>Starting Emission Rate[a] (g/m²-min)</td>
<td>Ending Emission Rate[a] (g/m²-min)</td>
<td>Emission Above Back-ground[a] (g)</td>
<td>Total Emission From Block (g)</td>
</tr>
<tr><td>A-28-e</td><td>0.0050</td><td>0.0010</td><td>6.5</td><td>6.8</td></tr>
<tr><td>A-29-e</td><td>0.0045</td><td>0.0010</td><td>5.4</td><td>5.6</td></tr>
<tr><td>A-30-e</td><td>0.018</td><td>0.0010</td><td>49</td><td>51</td></tr>
<tr><td>Avg</td><td>0.063</td><td>0.0010</td><td>20</td><td>21</td></tr>
</table>

[a] *Sample taken at Location 3. Emissions from Locations 1, 2, 4, and 5 were negligible compared to Location 3.*

Table 7.   Demonstration Test Results for Physical Properties

	Percent Moisture (%)	Bulk Density (g/cc)	Specific Gravity (g/cc)
Pre-Treatment			
Avg	30.2	1.52	2.56
Std Dev	7.9	0.09	0.09
Post-Treatment			
Avg	27.7	1.55	2.73
Std Dev	5.4	0.13	0.07

30

Appendix C
Process Description

The *in situ* steam/hot-air stripper is constructed of two major elements: the process tower and the process train. The process tower includes two hollow augers that drill into the soil to be treated. The process train consists of two systems which operate in conjunction during the treatment of the soil: the process gas treatment system and the condensed liquids treatment system or distillation system. The gas treatment system provides the conditioning of steam/hot-air/volatiles so that the air can be reintroduced into the process. The liquids treatment system separates the condensed steam from the condensed volatile organics by distillation. The organic waste is then collected for disposal or recycling and the condensed steam is used to supplement the cooling system.

The Process Tower

The process tower, shown schematically in Figure 4, consists of five major components:

- the treatment shroud,
- the kelly bars,
- the cutter bits,
- the rotary table, and
- the crowd assembly.

Together, these components loosen the soil, inject the steam/hot-air, and collect the stripped volatiles from the soil.

The cutter bits are attached to the end of each kelly bar. A set of mixing blades is also attached above the cutter bits. Each kelly bar is thus equipped with two sets of opposing blades (cutter bits and mixing blades) positioned at 90 degrees from each other, as shown in Figure 4. The cutter bits have nozzles for injection of steam/hot-air into the soil. Mechanical power is provided to the kelly bars by the rotary table and crowd assembly.

The steam and hot air raise the temperature of the soil mass to 170 to 180°F, thereby increasing the vapor pressure of the volatiles, volatilizing them away from the soil particles, and allowing them to be transported to the soil surface by the action of the steam/hot-air and an applied vacuum. The cutter bits are moved vertically to selectively treat areas of greater organic contamination as detected by in-line instrumentation. This treatment cycle procedure is repeated until the contaminant levels in the soil are satisfactorily reduced. The treatment procedure facilitates overlapping treatment of all depths of the block to ensure adequate exposure of the contaminants to the steam and hot air.

Upon emerging from the soil surface, the volatilized vapors and hot air (off-gas) are collected beneath the treatment shroud and are then passed on to the gas treatment system of the process train.

The Gas Treatment System

The gas treatment system consists of the following major equipment:

- the scrubber,
- the cyclone separator,
- the cooling system,
- the carbon adsorption system, and
- the compressors.

Particulate matter entrained in the process airstream is removed in the scrubber. The process airstream is then directed to a cyclone separator to remove the water droplets introduced to the airstream in the scrubber and water resulting from condensing steam. The water collected in the separator is directed to the distillation system for purification.

After this initial conditioning, the airstream is subjected to three stages of cooling by heat exchangers. These stages remove water vapor and the volatile compounds from the airstream by condensation. Condensate that forms inside the coolers is accumulated and directed to the distillation system.

The process airstream from the cooling system is passed through the carbon beds to remove volatile organics. There are two carbon adsorption vessels which are used alternately. While one vessel is used for adsorption of volatiles in the airstream, the other vessel undergoes regeneration of its carbon bed. The liquids produced from regeneration are directed to the distillation system.

The airstream exiting the carbon adsorption system is drawn through the intake filter of a two-stage reciprocating compressor. The compressor is designed to increase the air pressure from atmospheric to 250 pounds per square inch gauge (psig), thus increasing the discharged air temperature to approximately 275°F. This compressed air is passed back through the kelly bars to the ground to strip more contaminants from the soil.

The Distillation System

The condensates that are generated by the cooling system, the cyclone separator, and the regeneration of activated carbon are first passed through a 4-stage coalescer/separator.

Water contaminated with light organics is pumped from the coalescer/separator to the distillation tank. The distillation tank separates the remaining volatile components from the water. The vaporized volatile components are removed from the distillation tank, condensed, and collected in the condensed organics holding tank.

An activated carbon filter is used to remove residual organics in the water prior to discharge to the cooling tower sump. The carbon filter is regenerated, and the organics removed are discharged to the condensed organics holding tank.
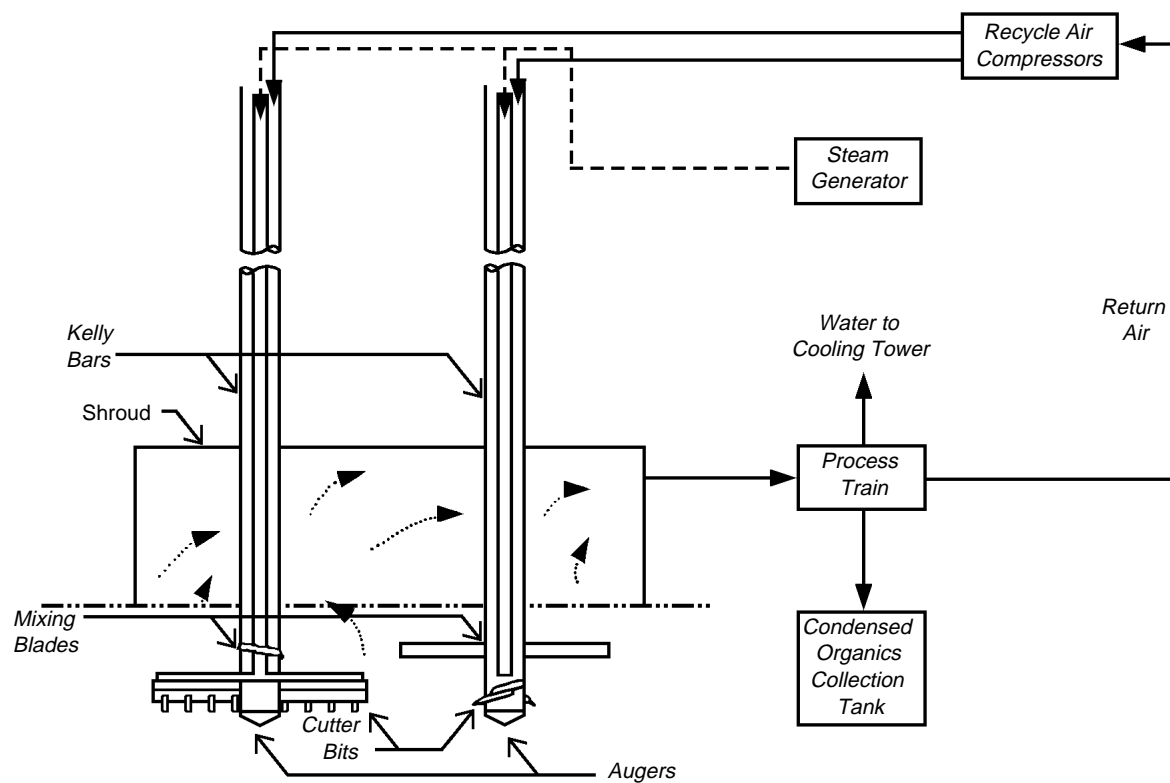

Figure 4.   Schematic of the process tower.

Appendix D
Case Studies

Baseline Testing [3]

Description

Baseline Testing was conducted by TTUSA to evaluate the effectiveness of *in situ* steam/hot-air stripping in removing hydrocarbons from the soil at the GATX Annex Terminal site. The Baseline Testing activities included:

- Treatment of 10 blocks.

- Collection of pre- and post-treatment samples.

- Collection of soil vapor emission data before and during the treatment of the 10 blocks.

- Condensate analysis to evaluate the hydrocarbons collected by the *in situ* steam/hot-air stripper process treatment train.

Testing Protocol

The pre-treatment soil samples were obtained from 24 borings in Areas A, B, and D: 2 in each of the 10 blocks to be treated and 4 in locations west of the area to be treated. Post-treatment soil samples were collected from 14 borings located in 10 treatment blocks: one boring per block in Areas A and D, and two per block in Area B. Soil vapor emissions monitoring was also conducted during Baseline Testing.

Major Conclusions by TTUSA Based on Baseline Testing

Based on a pre- and post-treatment chemical analysis, the *in situ* treatment had a number of effects on the treatment blocks. A significant reduction in the concentration of VOCs was observed for all test blocks. The mechanism for the reduction appeared to be *in situ* volatilization and recovery of the volatilized material. This is substantiated by the calculations performed on chemical analysis data, which show the mass of VOCs removed from the soil as approximately equal to the mass of VOCs collected in the holding tank. Differences between removal and collection can be attributed to sampling uncertainties and loss to the atmosphere. The target cleanup level, a final VOC concentration of less than 100 ppm, was achieved in 8 out of 10 of the blocks treated.

A reduction in the concentration of SVCs was indicated in all treatment blocks. The mechanism of removal cannot be supported by the analysis performed, since calculations from the analyses show that only a fraction of a percent of the SVCs removed from the soil were collected in the condensate.

The comparison of pre- and post-treatment data indicated that VOCs with lower boiling points were more effectively removed by the *in situ* steam/hot-air stripping process than higher boiling VOCs. Frequently, compounds with boiling points below 175°F (80°C) were removed to levels which could not be detected. When they were detected, these low boiling compounds exhibited significant reductions in concentration. Those compounds with boiling points above 175°F also exhibited significant reductions in concentration, but the concentrations were less frequently reduced to below the detection limit.

The average values of wet and dry soil density increased following the treatment. The average moisture content of the soil decreased after treatment.

Overall, the treatment process increased the soil vapor emissions within and directly adjacent to the area under treatment. Data indicate that the increase in emissions does not appear to be significant.

Occasionally, compounds which were not detected in pre-treatment samples were found in the post-treatment samples. Possible explanations for this include: (1) decreased detection limits due to overall lowering of concentration; (2) chemical alterations of compounds because of reactions occurring during treatment; and (3) redistribution of compounds within the block.

Data Summary

Soil emissions data show an average undisturbed emission rate of 2.0×10^{-3} g/min-m^2. During treatment, the level rose to an average emission rate of 3.2×10^{-2} g/min-m^2 at the soil/shroud interface, and an average of 2.4×10^{-2} g/min-m^2 at 2 feet away from the shroud perimeter. Comparisons of emission rates indicated that Area D had a lower overall emission rate both before and during treatment. This may be an effect of the clay type of soil found in Area D. While the data shows an order of magnitude change of emissions from the soil before treatment to during treatment, the actual increase, in pounds of emitted chemicals on a daily basis, cannot be calculated from the data collected since emissions were not monitored after treatment of a block was completed. However, it may be only a small increase over the baseline.

The mass of VOCs and SVCs collected by the process train and removed from the soil were calculated from the chemical analysis data gathered during the test. Table 8 presents these results; Table 9 presents the results of the physical analyses. For VOCs, the mass removed from the ten blocks (296 lbs) is close to the amount captured in the condensed organic holding tank (265 lbs). This represents approximately 90% closure. It is likely that the 10% difference can be accounted for by measurement uncertainties and losses within and from the system. The SVC mass balance, however, does not close in such a manner. The calculated removal from the soil of the first six treatment blocks in the Baseline Testing shows 1,018 lbs of SVCs removed from the soil, but the amount of SVCs in the condensed organic holding tank was only 2.1 lbs (0.2% closure).

Process Improvement and Soil Vapor Emissions Tests [4]

Description

Utilizing recently modified equipment and procedures, Process Improvement and Soil Vapor Emissions Tests (called "Remediation Improvement Tests" by TTUSA) in treatment Area D were initiated to evaluate the effect of moving the air manifolds from the top of the blades to the back of the blades on the augers and to evaluate the effect of utilizing both a gas chromatograph (GC) and a flame ionization detector (FID), rather than an FID alone, to determine organic contaminant levels in the soil blocks during treatment. The tests focused on three treatment blocks. Test activities consisted of:

- The collection of pre- and post-treatment soil samples from the three subject treatment blocks.

- The treatment of the three subject treatment blocks.

- The collection of soil vapor emissions data, during and after treatment.

Testing Protocol

Pre-treatment soil samples were collected from a total of six borings in the three treatment blocks (two per block). Post-treatment samples were collected from a total of three borings (one per block). Soil temperature was monitored after treatment to determine the rate that heat dissipated from the soil. Soil vapor emissions were also measured.

Major Conclusions by TTUSA Based on Process Improvement and Soil Vapor Emissions Tests

Modifications to equipment and treatment procedures resulted in a 3.8% increase in removal for tetrachloroethene and a 3.8% decrease in removal for total VOCs. This indicates that there was no significant change in treatment efficiency due to the modifications in the augers and the treatment procedures.

Soil vapor emissions data implies that treatment by the *in situ* steam/hot-air stripping unit did not result in any significant fugitive emissions during testing. Comparison of the post-treatment soil vapor emissions indicates that using a

Table 8. *Chemical Analysis Results for Baseline Testing*

Soil

Area	A	B	D	All
Pre-Treatment Soil				
Avg VOC (ppm)	1,114	1,353	3,954	2,140
Avg SVC (ppm)	3,775	12,116	1,014	5,635
Post-Treatment Soil				
Avg VOC (ppm)	12	30	140	61
Avg SVC (ppm)	627	1,766	85	826
Percent Reduction:				
Avg VOC	99%	98%	96%	97%
Avg SVC	83%	85%	92%	85%

Collected Organics

	VOC Concentration	SVC Concentration
DHS Sample		
Aqueous Layer (mg/L)	1,809	192
Organic Layer (mg/L)	1,000,000	21,450
TTUSA Sample		
Upper Layer (mg/L)	4,499	NA[a]
Middle Layer (mg/L)	3,452	NA
Lower Layer (mg/L)	587,000	NA
Average (mg/L)	198,317	

[a] NA - Not analyzed

Table 9.   Physical Analysis Results for Baseline Testing

Area	A	B	D
Bulk Density *(lb/ft³)*			
Pre-Treatment	75.0	75.3	43.4
Post-Treatment	96.5	88.0	75.0
Percent Increase	29%	16%	73%
Moisture *(%)*			
Pre-Treatment	37.3	43.4	88.2
Post-Treatment	25.4	29.5	40.8
Percent Decrease	32%	32%	54%

clean layer of soil to cover treated treatment blocks reduces fugitive emissions by over 50%.

Data Summary

Review of the pre- and post-treatment chemical analyses for tetrachloroethene demonstrated an average removal of 91.2%. Average percent removal for total VOCs was 94.1%. These results are very comparable to chemical analyses of samples taken during the Baseline Test, prior to the subject modifications.

The average soil vapor emission during treatment was 0.16 ppm. This is less than the average pre-treatment vapor emission concentration for Area D as determined in Baseline Testing (0.23 ppm). Post-treatment soil vapor emissions from an uncovered, treated block averaged 2.64 ppm, while emissions from a soil-covered block averaged 1.13 ppm, 57.2% less.

Mixing, Treatment, and Downward Migration Tests [4]

Description

Mixing, Treatment, and Downward Migration Tests (called "Containment Tests" by TTUSA) were conducted on four treatment blocks in treatment Area B in a progression of activities comprised of:

- The collection of pre- and post-mixing and post-treatment samples from the subject treatment blocks.

- The mixing of four treatment blocks, injecting only hot air.

- The placement of fluorescein dye packets in four treatment blocks, the treatment of three treatment blocks, the collection of soil samples from all four blocks for fluorescein dye evaluation.

- The collection of soil vapor emissions data during and after treatment.

Testing Protocol

Pre-treatment soil samples were collected from six borings in three blocks. These three blocks underwent mixing proce-

dures; a fourth block was also mixed as a control block. Post-mixing samples were collected from six borings in the three test blocks. A 50-gram packet of crystalline fluorescein dye was placed in each of 20 borings drilled in four (three plus one control) blocks prior to treatment. Post-treatment soil samples were collected from the three test blocks. One boring was collected from each block. Soil vapor emissions were measured during and after the treatment.

Major Conclusions by TTUSA Based on Mixing, Treatment, and Downward Migration Tests

Based on average VOC concentration data and treatment time data, it appears that mixing with only hot air injection caused a decrease in the concentration of VOCs. The percent decrease appeared to increase with time. A "Student's t-Test", however, which takes into account the standard deviation of the data, indicated that mixing procedures had little or no effect on the concentration of VOCs. Conclusive data for the effect of mixing on SVC concentration was not obtained during these tests, and a "Student's t-Test" of the data indicated that there was no treatment effect [1].

The downward migration of fluorescein dye due to soil treatment did not appear to be significant. The indicated extent of dye migration is consistent, even in the treatment blocks treated with steam and hot air. Because fluorescein dye is generally more soluble than the VOCs or SVCs found on-site, it is reasonable to assume that any downward migration of the VOCs and SVCs would be less than the dye. Therefore, the extent of downward migration of VOCs and SVCs was not significant. The data does not conclusively indicate if depth of dye migration changes with time.

Data indicates that treatment with steam and hot air had a significant effect on reducing VOC concentrations. Statistical analysis of the data supports this conclusion. Data on the reduction of SVCs in the soil was inconclusive. A "Student's t-Test" indicated that there was no change in the SVC concentration. Statistical analysis of samples taken from below the treatment zone indicated that there was no change in the concentration of either the VOCs or the SVCs.

Soil vapor emissions during treatment averaged less than pre-treatment vapor emission concentrations for Area B as determined in the Baseline Tests. Again, this implies that

treatment by the *in situ* steam/hot-air stripping unit did not result in significant fugitive emissions during testing. Soil vapor emissions decreased further after treatment was completed.

Data Summary

After the mixing tests with only air, treatment blocks B-48-g, B-49-g, and B-50-g showed the following decreases in average VOC concentrations based on the analysis of pre-mixing and post-mixing samples: 16%, 75%, and 79%, respectively. After mixing activities, SVC concentrations increased by 122% for block B-48-g, decreased by 93% for block B-49-g, and decreased by 70% for block B-50-g. Associated mixing times for the respective treatment blocks were 21 minutes, 11 minutes, and 100 minutes.

Average dye penetration depth in block B-46-g (treated with hot air only) for 1, 7, and 16 days after treatment was 4.1 feet, 0.1 feet deeper than the treated depth. Average dye penetration depth over the entire time frame in blocks B-48-g, B-49-g, and B-50-g (treated with both steam and hot air) was 4.7, 5.5, and 4.5 feet, respectively. Dye migration depth averaged 0.6 feet deeper than the treated depth for blocks B-48-g, B-49-g, and B-50-g.

Within the treatment zone, average VOC concentrations after treatment with air and steam showed a 89%, 91%, and 100% decrease in the VOC concentrations from their corresponding post-mixing levels for blocks B-48-g, B-49-g, and B-50-g, respectively. Data on the reduction of SVCs in the soil were inconclusive; results showed a 33% decrease, 59% increase, and 9% increase in the SVC concentrations from their corresponding post-mixing levels for blocks B-48-g, B-49-g, and B-50-g, respectively.

The average soil vapor emission around the shroud perimeter during treatment was 0.58 ppm. This is less than the average pre-treatment vapor emission concentration of 1.85 ppm for Area B as determined in the Baseline Tests. Average post-treatment soil vapor emissions from within the treated blocks B-48-g, B-49-g and B-50-g and from around the perimeter of these blocks ranged from 4.78 ppm at zero minutes after treatment to 1.72 ppm at 291 minutes after treatment.

TTUSA Bench-Scale Tests [4,5]

Description

As a follow-up on information generated from previous tests, several Bench-Scale Tests were performed by TTUSA. The Bench-Scale Tests were used to evaluate the response of microbial organisms to treatment as well as the potential for the removal of semivolatile compounds by various mechanisms including steam distillation, hydrolysis, oxidation and reduction. Test activities were comprised of:

- The collection of treated and untreated soil samples for microbial evaluation.

- The evaluation of microbial activity in treated and untreated soil.

- A Scoping Bench-Scale Test to evaluate the potential for hydrolysis of SVCs.

- Sampling of the carbon beds and the liquid organics held in the liquid storage tank to examine the locations and quantities of SVCs captured in the full-scale *in situ* steam/hot-air equipment.

- Five Contained-System Tests to explore the fate of semivolatiles: three Spiked Soil Tests and two Contaminated Soil Tests.

Testing Protocol

The microbial evaluation was conducted to assess the effect of the steam/hot-air stripping process on the existing microbe population and the potential for the microbe population to re-establish itself after treatment. Six soil samples were obtained from duplicates of samples previously collected from treated soil and four samples obtained from duplicates of soil samples previously collected from untreated soil.

Soil from each sample was used to prepare an aliquot for dilution. One milliliter from each dilution was then transferred to a petri dish and warm nutrient agar was added. The contents of the petri dish were thoroughly mixed, allowed to solidify, and then incubated for 48 hours at 30°C. Following the incubation period, visible colonies were counted to determine the number of viable organisms. The 6 petri dishes containing organisms from the treated soil were then incubated for an additional 7 days and enumeration procedures repeated to determine the number of viable organisms after treatment.

The Scoping Bench-Scale Test for hydrolysis was conducted on contaminated soil from the GATX Annex Terminal site exhibiting total SVC concentration of 887 ppm. A 470-g aliquot of soil, taken from a well-mixed 2-kg soil sample from treatment area B, was heated in water to 170°F (77°C) and held at that temperature for 1 hour. The system was open to air, so no vapors were captured. Analysis for both VOCs and SVCs was performed on samples of the pre- and post-treatment soil and on the water remaining at the conclusion of the test.

To examine the quantities of SVCs captured and their respective locations of accumulation in the full-scale equipment, samples were collected from the carbon beds and from the liquid storage tank and were analyzed for semivolatile compounds.

A series of five Contained-System Tests were also performed. A laboratory-scale *in situ* steam/hot-air stripper simulating field treatment conditions was used for these tests. Tests numbered 1, 2, and 5 (Spiked Soil Tests) were performed on clean soil from the site which had been spiked with known amounts of the major SVCs of interest: bis(2-ethylhexyl)phthalate, butyl cellosolve, butyl carbitol, 2-phenoxyethanol, and glycol ether. Tests 3 and 4 (Contaminated Soil Tests) were performed on contaminated site soil from treatment block B-48-g. For each run, approximately 5 gallons of soil were treated with 1 scfm of air and approximately 0.25 lb/min of steam, maintaining the temperature of the soil at 176°F (80°C). In all of the Contained-System Tests, samples of the pre- and post-treatment soil and of the condensed liquid were analyzed for SVCs. A barium chloride trap was analyzed in Tests 2 and 3, but since it contained little contamination and

showed no Carbon Dioxide capture, its use was discontinued in the subsequent tests. For all of the Contained-System Tests, the carbon bed from the bench-scale apparatus was sampled and analyzed for VOCs; it was also analyzed for SVCs in Test 5 in an attempt to improve the SVC mass balance.

Major Conclusions by TTUSA Based on Bench-Scale Tests

Based on the soil samples collected in Area B, the number of microbe colonies grown after 48 hours of incubation appears to indicate that treatment using the steam/hot-air stripping process causes microbe populations to decrease. Evaluation of the potential for microbial regrowth in Area B indicated that, at an optimal temperature of 86°F (30°C), the number of microbe colonies increased after an incubation period of 168 hours in all cases. This indicates that at a proper temperature, the microbial populations in previously treated soil are capable of regrowth. Evaluation of the microbial regrowth data showed higher potential for regrowth in Area D (clayey soil) than in Area B. Microbial growth is anticipated to be inhibited for approximately 4 weeks following treatment, while the soil temperature drops to a favorable range for growth of microbes.

The biological activity from microbe population in site soil will not significantly reduce the hydrocarbons at the site. Much higher microbe populations are necessary in order to cause a significant decrease in the concentration of hydrocarbons due to biological oxidation or reduction.

The results of the Bench-Scale Tests show agreement with the full-scale treatment data, exhibiting removals of SVCs of 46% to 87%; the removals calculated during the Baseline Test were 64% to 94%. Obtaining this result in a contained system suggests that downward migration, biological activity, and dilution by mixing are not significant factors in the field treatment results. The field mechanisms of removal appear to be volatilization, steam distillation, catalytic decomposition, hydrolysis, and binding to the clay in the soil.

The SVC mass balance performed as part of the Contained-System Tests was poor, similar to that performed for the full-scale field tests. One possible cause of this is a reaction of the phthalate compounds, catalyzed by the clay in the soil. The expected result of such reactions would be phthalate salts which are chemically bound to the soil; and alcohols which would decompose and dehydrate to form C_8 - C_{15} aliphatic hydrocarbons.

Unlike the full-scale field tests, the VOC mass balance was also poor. The carbon bed analyzed contained little of either VOCs or SVCs. This raises some questions about the nature of the contaminants because the carbon bed is believed to be able to catch any residual contamination before it enters the atmosphere. Since VOCs do not bind to the soil, it is postulated that both SVCs and VOCs are forming aerosols and escaping through the carbon beds without adsorption. Due to the recycling of the air in the field treatment system, escape of organic compounds is expected to be negligible for the full-scale unit.

Data Summary

The average number of colonies grown in untreated soil from Area B was 3.4 x 10^3 colonies per gram. In comparison, the number of microbe colonies grown after 48 hours of incubation in treated soil from the same area averaged 2.0 x 10^2 colonies per gram. Soil samples from Area B evaluated for regrowth after 168 hours of incubation exhibited increases in the number of microbe colonies ranging from 420% to 61,800%. Soil samples from Area D were also evaluated for regrowth after treatment. These samples exhibited changes in the number of microbe colonies ranging from -30% to 45,300%. The laboratory incubation temperature was 86°F (30°C). This is much less than the temperature of the soil during treatment which is approximately 176°F (80°C).

For the Scoping Bench Scale Tests, percent removal of SVCs was 69% and percent removal of VOCs was 81%.

The analysis of system carbon beds and the organics from the liquid storage tank showed moderate amounts of semi-volatile compounds and large amounts of C_8 - C_{15} olefins, substantiating the possibility that phthalates are undergoing reactions catalyzed by the clay.

Data from the Spiked-Soil Contained-System Tests is summarized in Table 10. Results of the Contaminated-Soil Contained-System Tests (3 and 4) indicate an average SVC removal of 53.5% and an average VOC removal of 82% as shown by Table 11.

Six-Week Deep Study [6]

Description

During the Six-Week Deep Study, the performance of the *in situ* steam/hot-air stripping unit was tested in the saturation zone to depths of 10 to 12 feet in Area A at the GATX Annex Terminal site. Previous operations in all other areas of the site had been restricted to treatment depths above the water table (located approximately 6.5 to 7.5 feet below the soil surface in this area).

Testing Protocol

Available data indicates that a total of 94 highly contaminated blocks were treated to 10 to 12 feet in the 23 days since the beginning of the 6-week test. One block was sampled prior to treatment. Post-treatment samples were collected at 5 to 7 feet and at 9 to 10 feet in approximately 5 borings. TTUSA also took four soil samples to provide guidance in relating real-time process operating parameters and soil chemistry. The samples were taken after the completion of treatment and the results of these analyses were compared to final FID readings.

Major Conclusions by TTUSA Based on Six-Week Deep Study

No operational problems of any kind occurred as a result of treating the saturated zone. The downhole temperature was often improved when treated below the water table. During treatment in the saturated zone, the *in situ* steam/hot-air stripper was able to operate between 205°F and 210°F downhole, without exceeding the 170°F limit for shroud gas temperature. For operations in the vadose zone, the downhole temperature limit is 175°F to 180°F.

Table 10. **Spiked-Soil Contained-System Tests Results**

Test Number	1	2	5
Pre-Treatment			
SVC spike (g)	193.5	[b]	247.1
Post-Treatment			
SVC in soil (g)	31.885	[b]	31.021
THC in water (g)	0.017[a]	[b]	47.293
THC in carbon bed (g)	NA[c]	[b]	0.632
TOTAL (g)	31.902	[b]	78.946
THC missing[d] (g)	161.598	[b]	168.154
Percent Removal	83.5%	[b]	87.4%

[a] *VOC only; water in Test 1 was not analyzed for SVC.*

[b] *Test 2 data was ignored due to serious errors encountered during chemical analysis.*

[c] *NA – Not analyzed.*

[d] *Pre-treatment spike (g) minus post-treatment total (g) equals THC missing (g).*

Table 11. **Contaminated-Soil Contained-System Tests Results**

Test Number	3	4
Pre-Treatment		
SVC (g)	30.987	30.987[a]
VOC (g)	9.376	9.376[a]
Post-Treatment		
SVC in soil (g)	16.758	12.112
SVC in water (g)	12.574	7.263
SVC in carbon bed (g)	NA[b]	NA
TOTAL SVC (g)	29.332[c]	19.375[c]
VOC in soil (g)	3.403	0.000
VOC in water (g)	0.133	0.670
VOC in carbon bed (g)	0.404	1.236
TOTAL VOC (g)	3.940	1.906
THC missing (g) based on SVC analysis	1.655	11.612
THC missing (g) based on VOC analysis	5.436	7.470
Percent Removal		
SVC	45.9%	60.9%
VOC	63.7%	100.0%

[a] *From an estimated weight, based on volume of container.*

[b] *NA – Not analyzed.*

[c] *This total excludes SVCs which may appear in the carbon bed since the carbon bed samples were not analyzed for SVCs.*

The removal rate of contaminants below the water table appears to be faster than in the previous treatment to 5 feet. This is due in part to the elevated downhole temperature. A second factor influencing the increased removal rate is the effect of sandy soil present in and below the water table. It is postulated that, in these areas, the water causes the treatment to act like a fluidized bed which improves the exchange and removal rates.

The continuous FID-versus-depth readings obtained when the unit's blades penetrate the soil may provide a qualitative characterization of the soil contamination chemistry profile. The *in situ* steam/hot-air stripper may, therefore, have poten-tial to determine the depth of contamination and thus the required treatment depth.

The FID/soil contamination correlation generated for use when treating to 5 feet does not apply in the saturation zone. Real-time soil samples indicate that residual soil contamination levels of only 30 to 60 ppm are possible with FID readings of 2,500 to 3,000 ppm. This is approximately two times the FID readings obtained in the vadose zone for treatment to the same levels.

Data Summary

Complete results on the 8240 and 8270 analyses were not available as of the date of this report. Results of the 8010 analyses show chlorinated hydrocarbon levels ranging from 24 to 60 ppm, with an average value of 39 ppm. The correlation between these levels and the final FID readings requires further investigation.

References

1. Science Applications International Corporation. August 18, 1989. "Demonstration Plan for Demonstration Tests on Toxic Treatments *In Situ* Steam/Hot-Air Stripping Technology, Volumes 1 and 2."

2. *Federal Register,* Volume 55, No. 61, March 30, 1990.

3. Harding Lawson Associates. March 8, 1989. "Baseline Calibration and Testing, Annex Terminal Site, San Pedro, California." A report prepared for GATX Terminals Corporation.

4. McLaren Engineering. November 30, 1989. "Six-Block Test Report, Annex Terminals Site, San Pedro, California." A report prepared for GATX Terminals Corporation.

5. "Toxic Treatments (USA), Inc. January 10, 1990. Part of the Disposition of Chemicals During and After Detoxifier Remediation." A Draft Report on the Bench-Scale Tests.

6. "Toxic Treatments (USA), Inc. February 1990." Four-Week Report on Using the Detoxifier to Treat in the Saturated Zone.